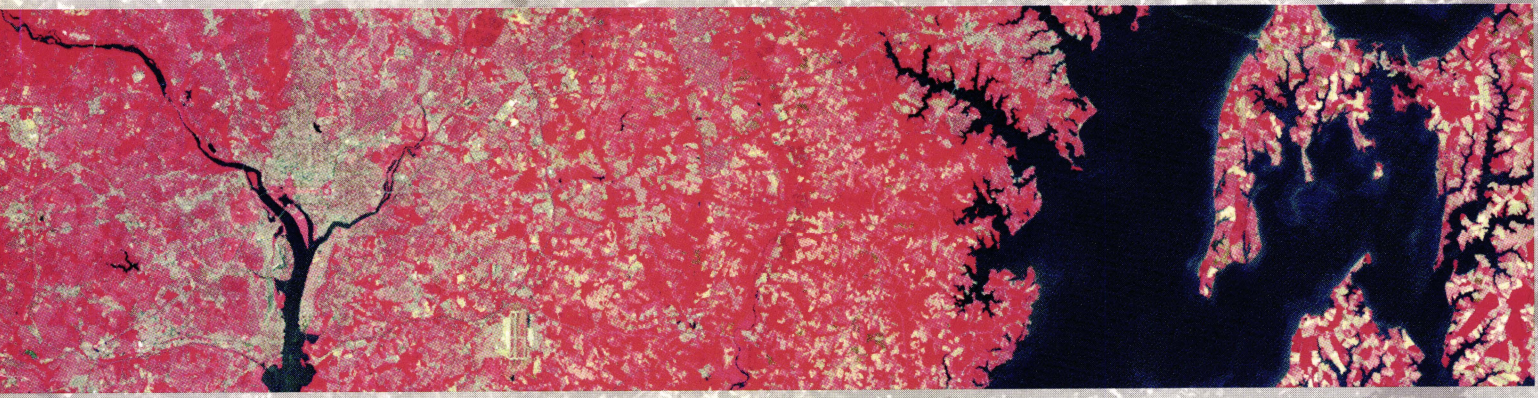
A Landscape Atlas of the Chesapeake Bay Watershed



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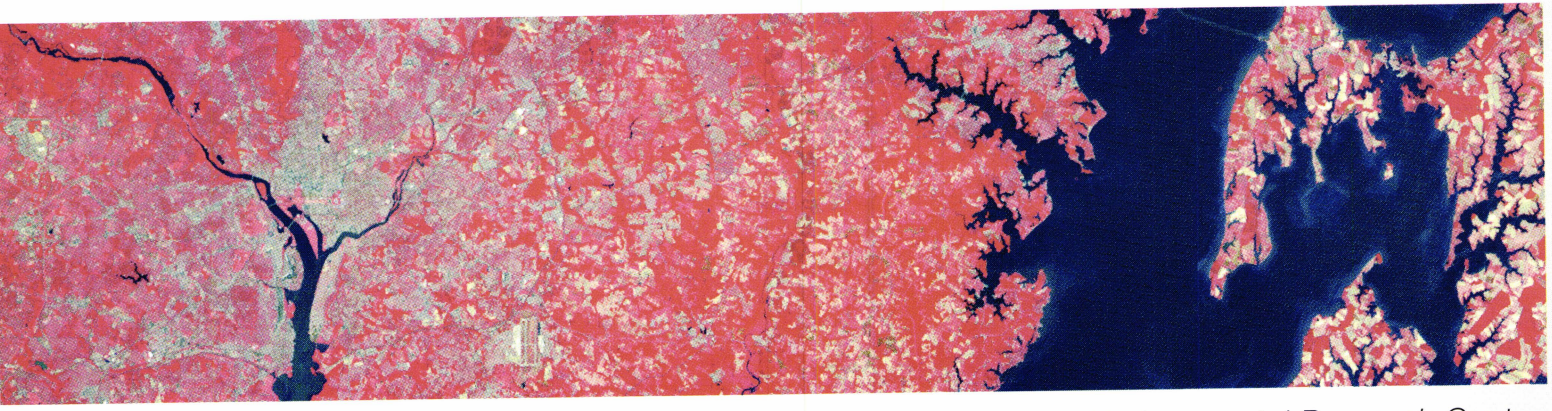

K.H. Riitters & J.D. Wickham, Environmental Research Center, Tennessee Valley Authority

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Disclaimer Statement

The purpose of this atlas is to show examples of how the principles of landscape ecology can be applied in regional-scale ecological assessments. The examples do not constitute a definitive assessment of ecological condition in the Chesapeake Bay region. There has not been a formal review of this atlas, and no official endorsements should be inferred. Mention of trade names does not constitute endorsement or recommendation for use.

On the cover:
False color composite of Landsat Multi-Spectral Scanner satellite images over the Chesapeake Bay region.

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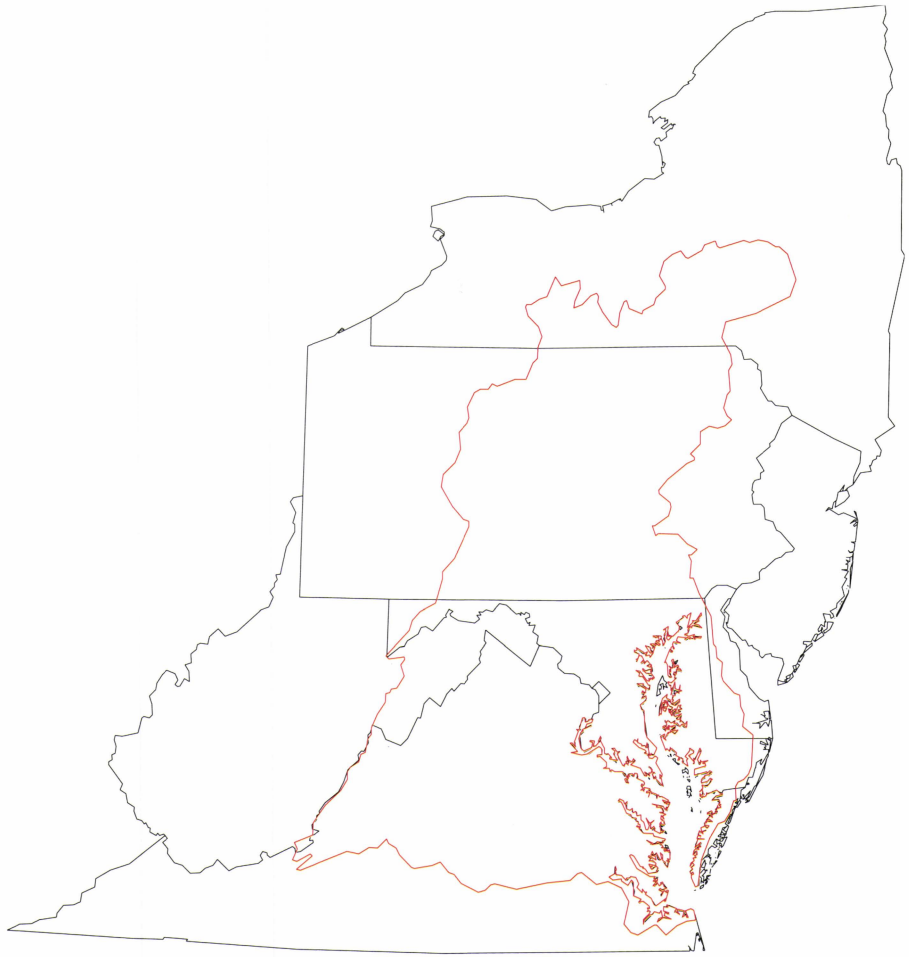
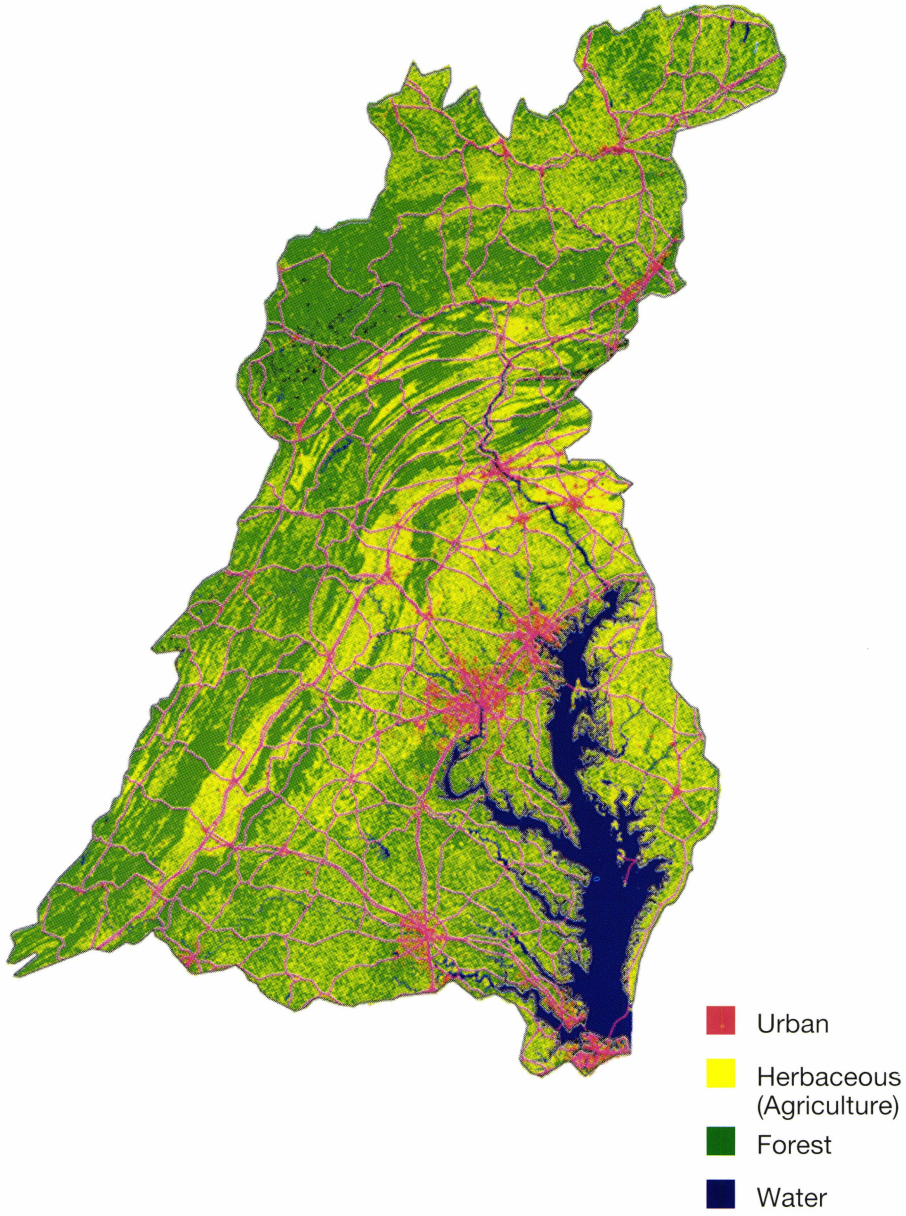
Introduction

What is the health or condition of ecosystems today? What are the impacts of pollution, climate change, and other environmental stresses? How do stresses interact with humans, ecosystems, and each other? What are the cumulative effects over large regions? What are the changes over time? These questions are being asked today in the Chesapeake Bay Watershed, an area of about 175,000 km^2 in the eastern United States, that extends from near Binghamton, NY, to the vicinity of Richmond, VA (right).

A "landscape" approach is needed to assess ecological conditions over such a large area. Some of the most important aspects of environmental change occur at the broad spatial scale of whole landscapes, and these cannot always be detected in small-scale studies. Because landscape patterns and trends are the context for the condition of embedded ecosystems, such information has proven useful for both local and regional assessments.



Above:
Location of the Chesapeake Bay Watershed in relation to the mid-Atlantic States.



Left:
Land cover map of the Chesapeake Bay Watershed, derived from Landsat Thematic Mapper images.

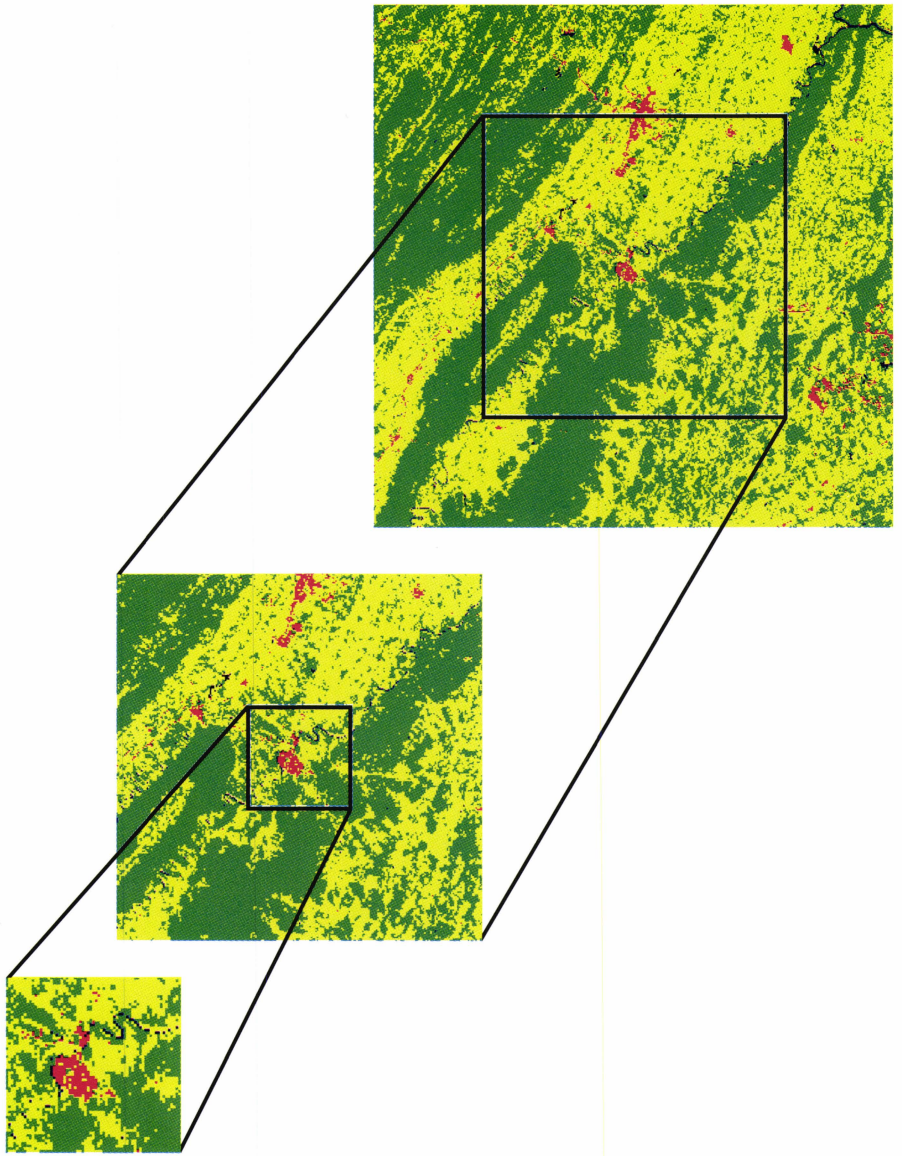
The potential now exists to begin landscape monitoring and assessments over very large geographic regions. In a cooperative project with the U.S. Environmental Protection Agency, scientists from the Tennessee Valley Authority are developing tools and techniques for landscape analysis. The purpose of this atlas is to illustrate some of these methods, and to introduce some concepts from the science of landscape ecology that are used in modern risk assessments.

Most of the examples in this atlas draw upon a regional map of land cover (left) which was derived from satellite images from the early 1990s. Using a high-tech approach, the power of remote sensing from orbiting satellites is combined with Geographic Information System (GIS) computer technology. Computers are used to measure indicators of regional-scale ecological conditions, to analyze these measurements, and to prepare tables and maps of the findings.

Landscapes at Many Scales

The famous American sportsman Yogi Berra once said that "you can see a lot by just looking." Look at the land cover map on page 3—you can easily see regional patterns of forest, agriculture, and urban areas. None of these regional patterns would be apparent if the map covered just a small part of the Watershed.

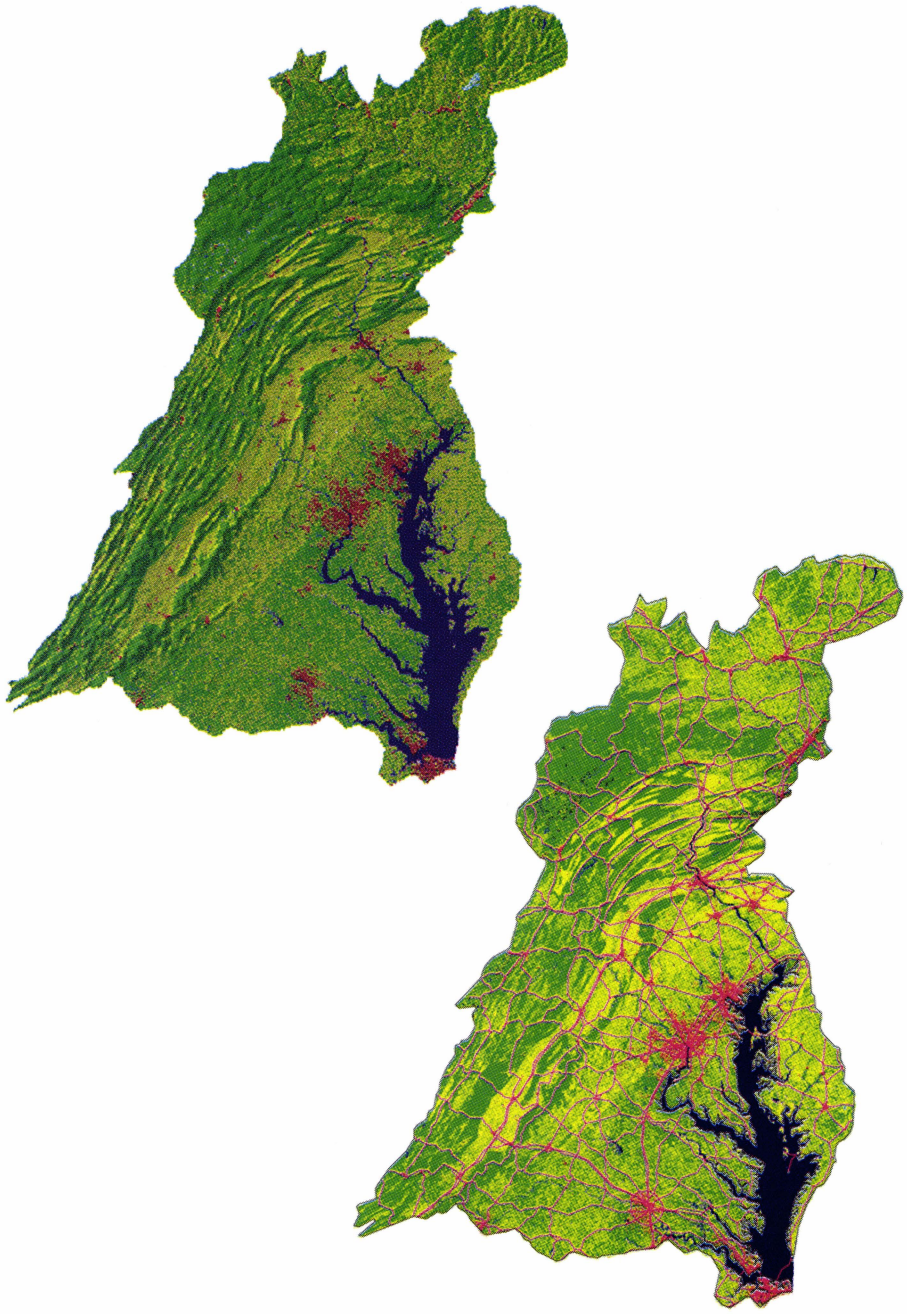
At finer scales, finer-scale patterns emerge, and landscapes are dominated by different types of land cover (right). Zooming in (or out) to see patterns at different scales is an important part of the landscape approach.



Right:
Multi-scale land cover patterns in the vicinity of Front Royal, Virginia. The area of the largest box is about 9000 km^2.

Associations Among Landscape Elements

Sometimes the patterns in different maps of the same area seem to fit together. With the help of a map of regional topography (top left), you can see that the valleys are mostly used for agriculture and the ridges are mostly forested. Where the topography is generally flat, there is a mosaic of both forest and agriculture land covers. With knowledge of major roads (bottom left), the urban areas appear as a connected network instead of as isolated patches. Using these associations to help interpret regional patterns is another part of the landscape approach.

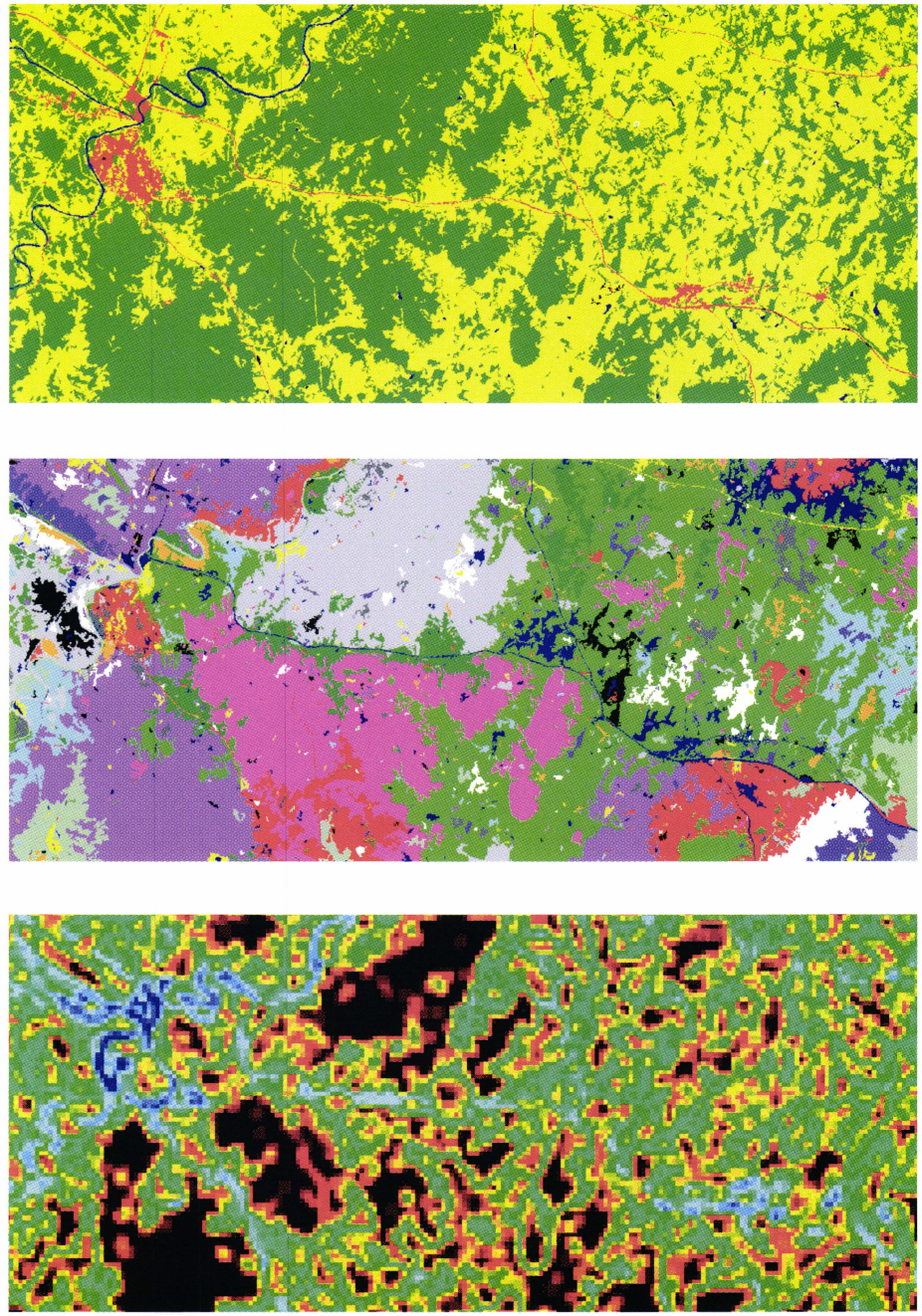


Left:
Land cover in relation to the topography *(top)*. Major roads of the Chesapeake Bay Watershed *(bottom)*.

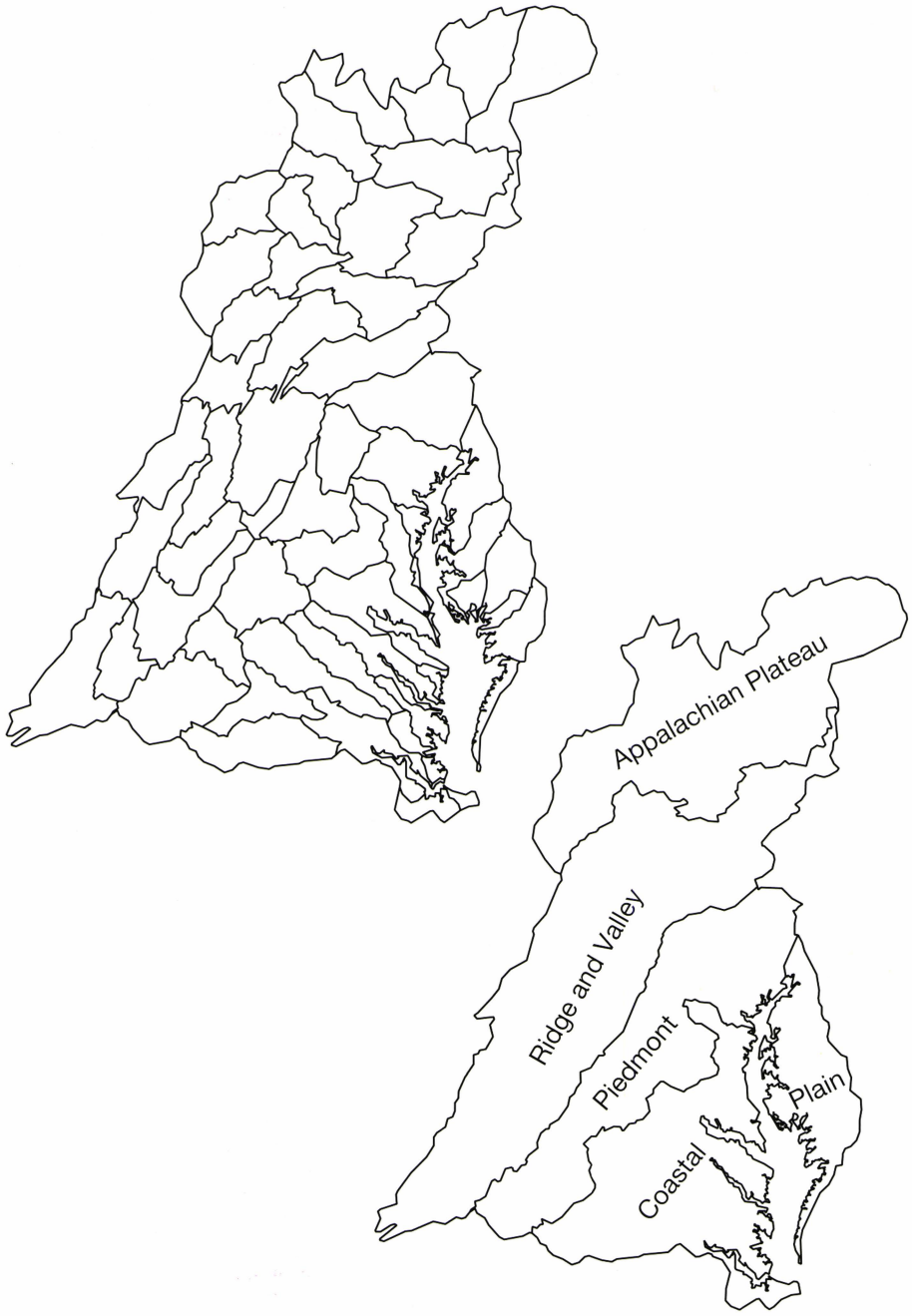
Landscape Patterns

Landscape ecologists use computers to discover patterns that humans cannot easily see. At right, the top map shows the land cover in the vicinity of Front Royal, VA. The middle map was made by drawing lines around clumps or patches of the same land cover. For display purposes, each patch was then shaded with a random color. The bottom map was made by color-coding the variety of land cover types contained in small "windows" placed on the land cover map. The brighter colors correspond to areas with higher variety of land cover types.

These different views may have meaning in terms of the way humans and wildlife view the landscape, or in terms of how different ecological processes take place over large regions. If so, then there is not a single correct way to view a landscape. A landscape approach to ecological assessment considers a variety of measurements.



Right:
Close-up views of patches *(middle)* and variety *(bottom)* derived from land cover *(top)*.



Left:
The Chesapeake Bay Watershed is made up of many smaller watersheds *(top)*, as well as, several physiographic regions *(bottom)*.

Landscape Summaries

The land cover map of the Chesapeake Bay Watershed is made up of about 285 million pixels ("pixels" is an abbreviation of "picture elements"), each representing 0.0625 ha of land area. This much information must be condensed or summarized for regional analysis. One method condenses pattern information into indicators which have some ecological relevance for assessment purposes. For example, average patch size is an indicator of how connected a landscape is, and land cover variety is an indicator of how diverse a landscape is. Landscape diversity and connectivity both have meaning when assessing animal habitat and movement patterns.

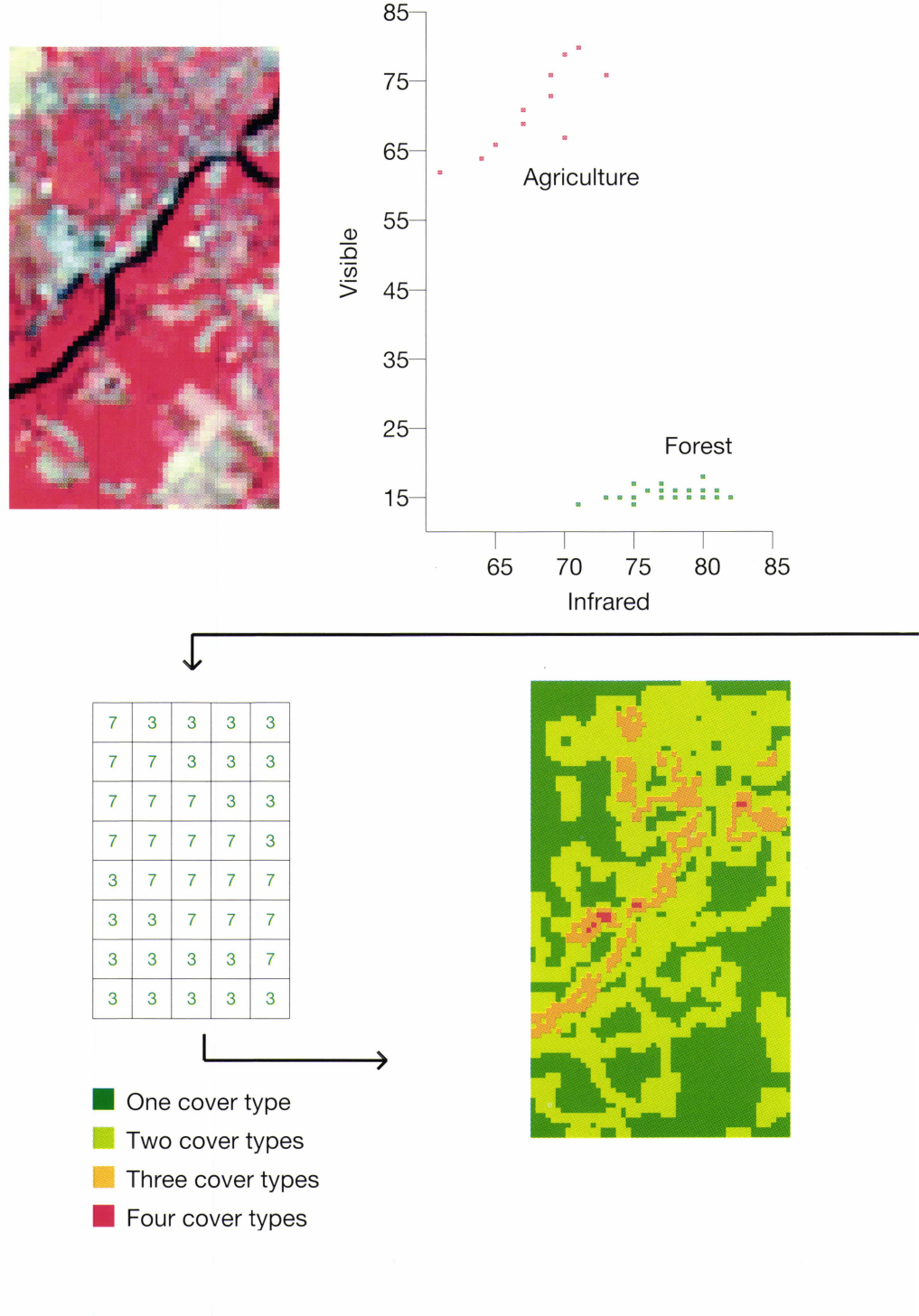
Another way to summarize land cover information starts by sub-dividing a whole landscape into pieces, like a jigsaw puzzle. An indicator is then calculated for each piece, and that piece gets the resulting score. When the puzzle is put together again, the regional picture reappears (but at a coarser resolution). Statisticians use the word "stratification" to describe the sub-dividing of landscapes for analysis.

A regional land cover map can be stratified in many different ways. The procedure is most efficient when the pieces are relevant to the question being addressed. Small watersheds (top left) are appropriate for questions about water resources because of the close relationship between streams and surrounding landscapes. Physiographic regions (bottom left) are sometimes used because vegetation and human land use patterns are associated with regional geophysical patterns.

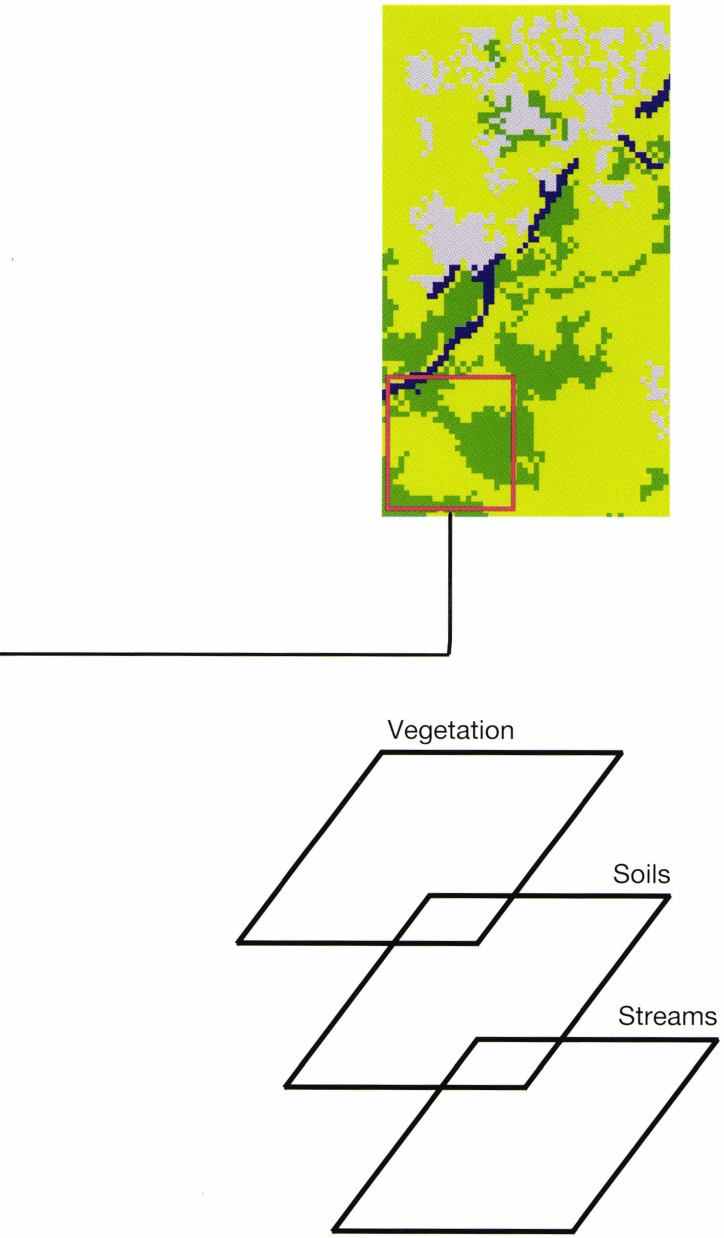
Methods

The figure at right illustrates a few of the techniques that are used to create and analyze land cover maps. Satellites take a series of pictures which record reflectance intensity at different wavelengths of light. The pictures can then be combined in different ways, for example, as a false-color composite image that looks almost like a regular photograph (top left and front cover). Different land cover types have characteristic reflectance values or spectral signatures (top center). These signatures are used to classify each pixel according to land cover type (top right). Map parameters, such as the number and types of land cover, depend on the satellite sensor, atmospheric conditions, and other factors.

Some land cover analyses require only simple procedures like counting the number of pixels of different types, measuring the perimeter and area of patches, or itemizing the ways that pixels of different types appear as adjacent pairs on the map. Indicator scores, for example land cover diversity, can be calculated from these measurements.



Right:
Some methods used to create and analyze land cover maps *(see text)*.



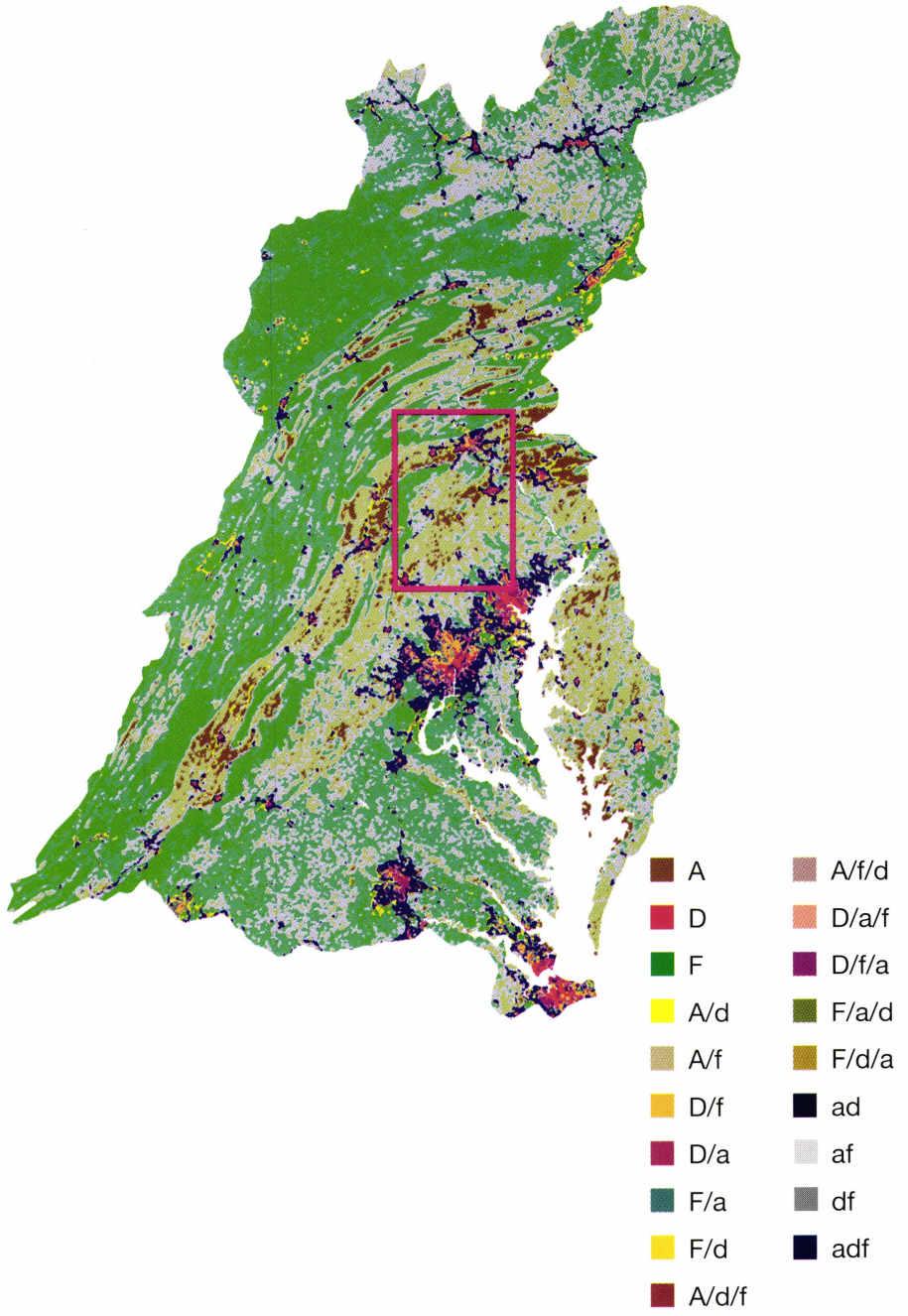
A powerful visualization tool involves making a new map which shows how an indicator changes over the region. To do this, a window is placed on the land cover map, as shown by the red box. The land cover in the box, represented by numbers (bottom left) is summarized by an indicator score. The color-coded score is then put into a new map at that place (bottom center). The surface map that emerges after placing the window everywhere on the land cover map shows the peaks and valleys of the indicator score over the region. This procedure is known as spatial filtering or a "sliding window" analysis.

Another common technique is to overlay maps of different themes (bottom right). Associations among different maps can be identified by comparing two or more indicator values for the same place. Maps of spatial associations can also be developed. The overlay technique is also used as a cookie-cutter to stratify a map into smaller watersheds or physiographic provinces.

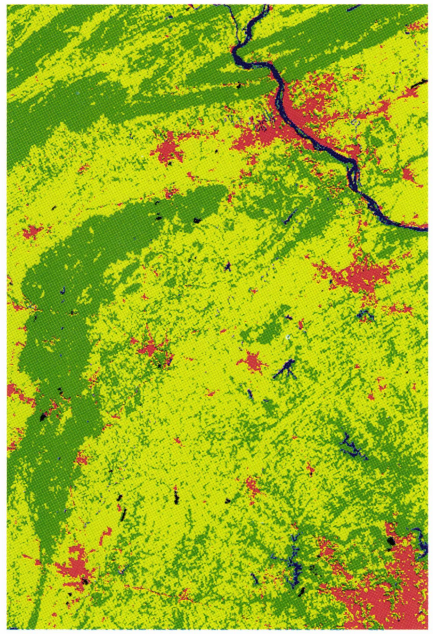
Human Landscapes

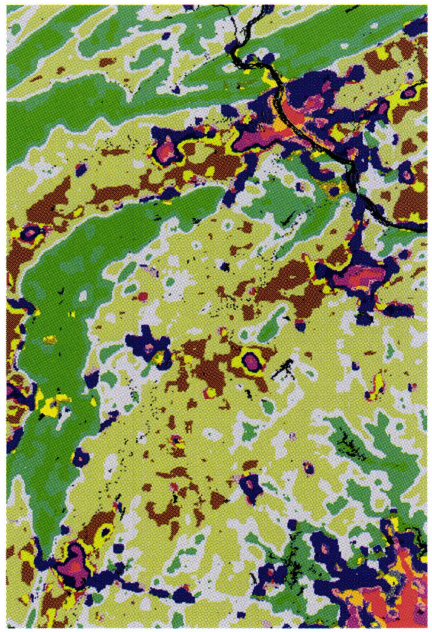
Humans structure the landscape for their purposes, and landscapes structure human activities. For example, humans may decide the shapes and sizes of individual agricultural fields, but regional patterns of topography, soils, and geology determine whether or not there can be fields at all. Because human-dominated landscapes are used for different purposes which impose different patterns, land use history is always important for understanding local landscapes. Regional-scale patterns are generated in geologic time by the same sorts of processes that create and destroy mountain ranges.

The interplay between humans and landscapes has created a tapestry of multi-scale patterns in the Chesapeake Bay Watershed. The following maps illustrate some of these patterns.



Right:
Landscape pattern types





Landscape Pattern Types

Landscapes may be categorized by landscape pattern types, or LPTs. LPTs are designed to identify repeating patterns associated with dominant land uses in an area. The pattern type of a landscape unit is determined by the relative proportions of forest, agriculture, and developed (urban) land cover it contains.

The map of LPTs for the Chesapeake Bay Watershed (left) has 19 classes. It was produced by using the sliding window technique to calculate the three land cover proportions in 410-ha windows. The relationship of LPTs to land cover is illustrated for an area northwest of Baltimore, MD, in the maps on the facing page.

LPT categories are labeled with combinations of the letters F, A, and D, referring to forest, agriculture, and developed land cover. The labels are interpreted as follows. An upper-case letter indicates an area with more than 60% of that land cover, and a lower-case letter indicates an area with less than 40% of that land cover. The ordering of letters corresponds to relative amounts of land cover in an area. If a land cover is less than 10% of an area, the corresponding letter is left out.

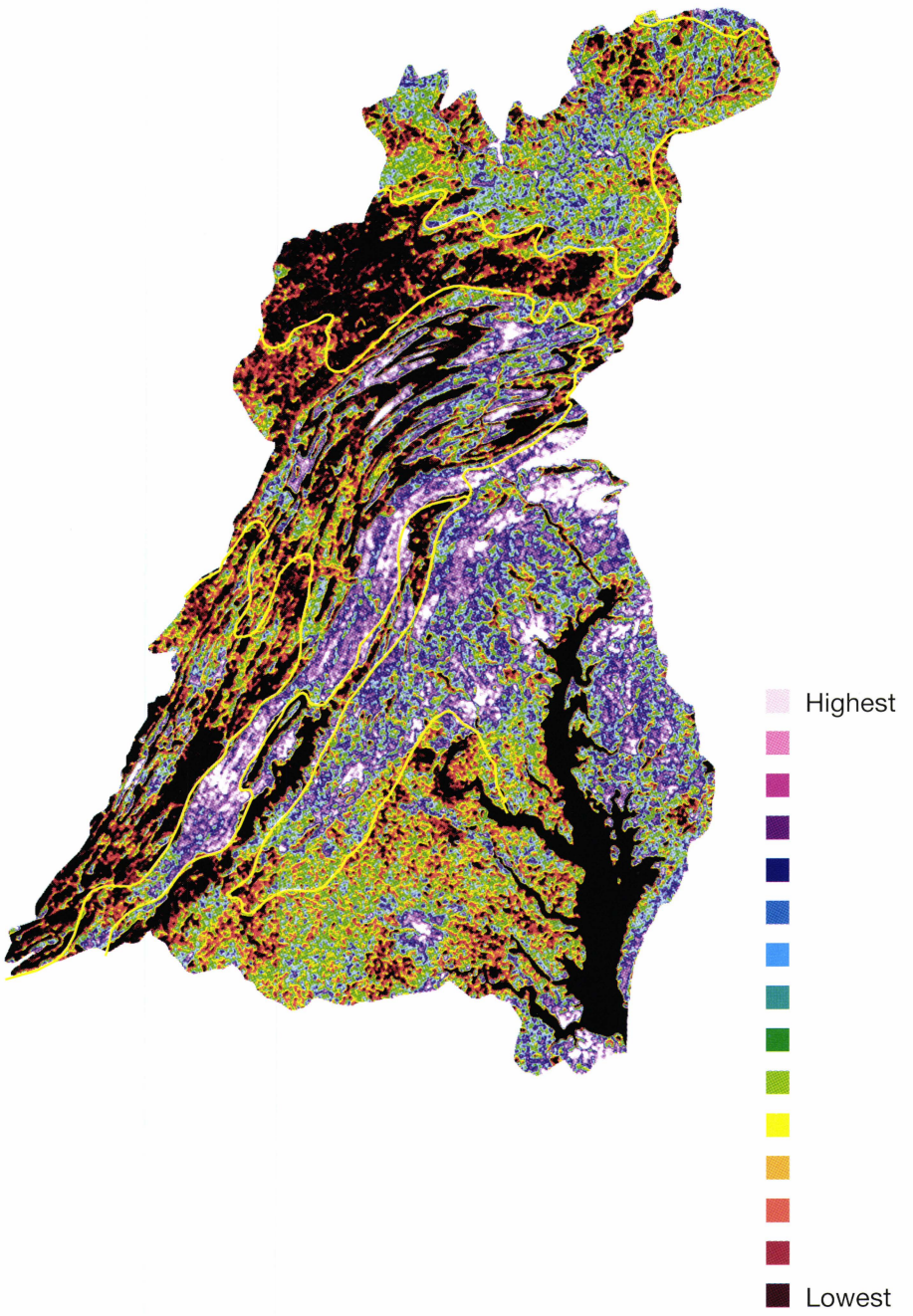
Left:
A close-up view of the relationship between land cover *(top)* and LPTs *(bottom)*.

Human Use Index

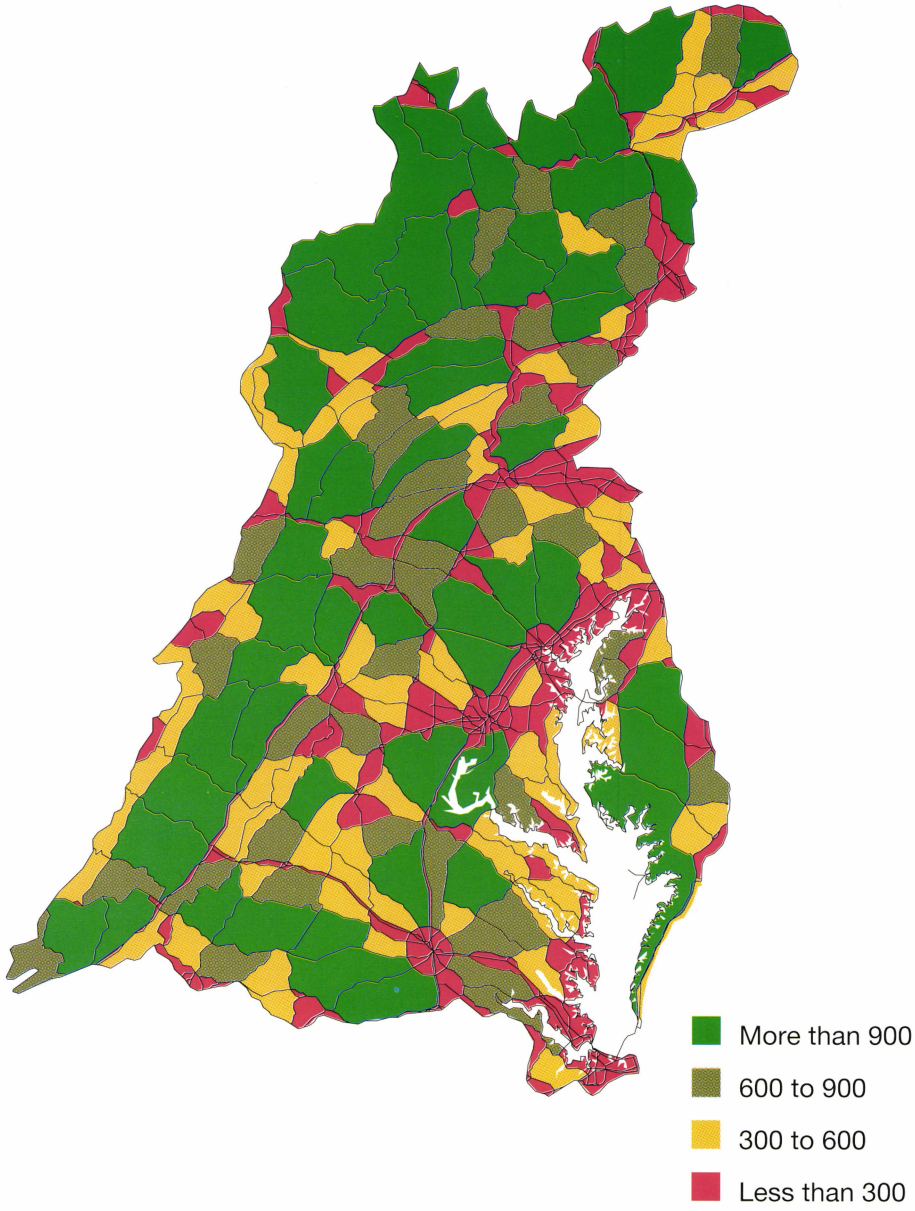
The proportion of an area that is developed or used for agriculture is a measure of human use known as the U-index. The surface map for the Chesapeake Bay Watershed (right) was produced by using the sliding window technique to calculate the U-index in 45-ha windows.

It is almost an adage that humans tend to simplify their environment. At landscape scales, however, the map displays complicated patterns of use. The scale at the transition from simple to complicated patterns might be a measure of the scale to which humans have structured a landscape, or conversely, the scale at which geophysical processes constrain human activity.

The boundaries of ecoregions are also drawn on the map. Ecoregions, like physiographic regions, comprise a regional-scale classification scheme that is used for ecological assessments. The apparent associations between ecoregions and the U-index are partly due to the use of land cover to define ecoregions. The demonstrated utility of ecoregions for regional assessments could be a result of the association with human use patterns.



Right:
Human use patterns in the Chesapeake Bay Watershed as measured by the U-index. High values indicate larger proportions of area in either developed or agricultural land covers. The boundaries of Omernik's ecoregions are also shown.



Roads

Roads and other transportation corridors are designed to connect the human-dominated elements of a landscape. The network of major roads in the Chesapeake Bay Watershed permits commerce and communication throughout the region.

Roads can also enhance or inhibit communication among ecological communities. As a simple analogy, think of a river system which facilitates the movement of fish but which prevents the crossing by mammals which cannot swim. Seral species (those adapted to disturbed sites) are often found along roads, and they can use road systems to spread throughout large regions. Many of the exotic plants and animals which are pests today are seral species that use roads in this manner.

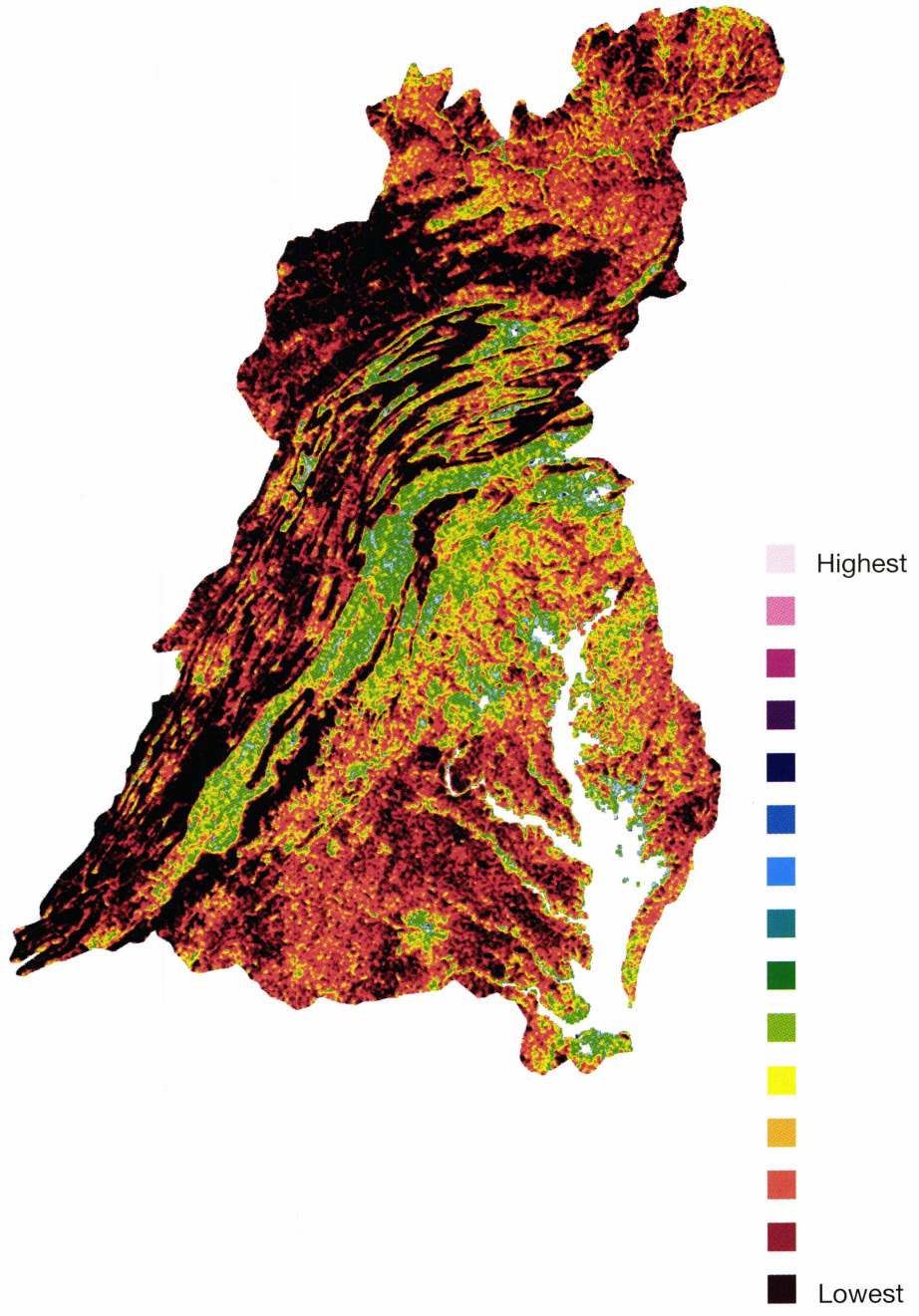
Other species view roads as barriers to movement. A species which is unable to cross a major road would view the landscape as a set of disconnected polygons (left). The long-term maintenance of regional biodiversity partly depends on communications among populations. Populations that are not able to cross major roads are genetically isolated from each other. Isolated populations which are lost cannot be replenished from outside if roads are a barrier to movement.

Left:
The polygons defined by major roads in the Chesapeake Bay Watershed have been shaded according to their area (km^2). The polygons at the edges of the Watershed would be larger if roads outside the Watershed boundary had been used to define them.

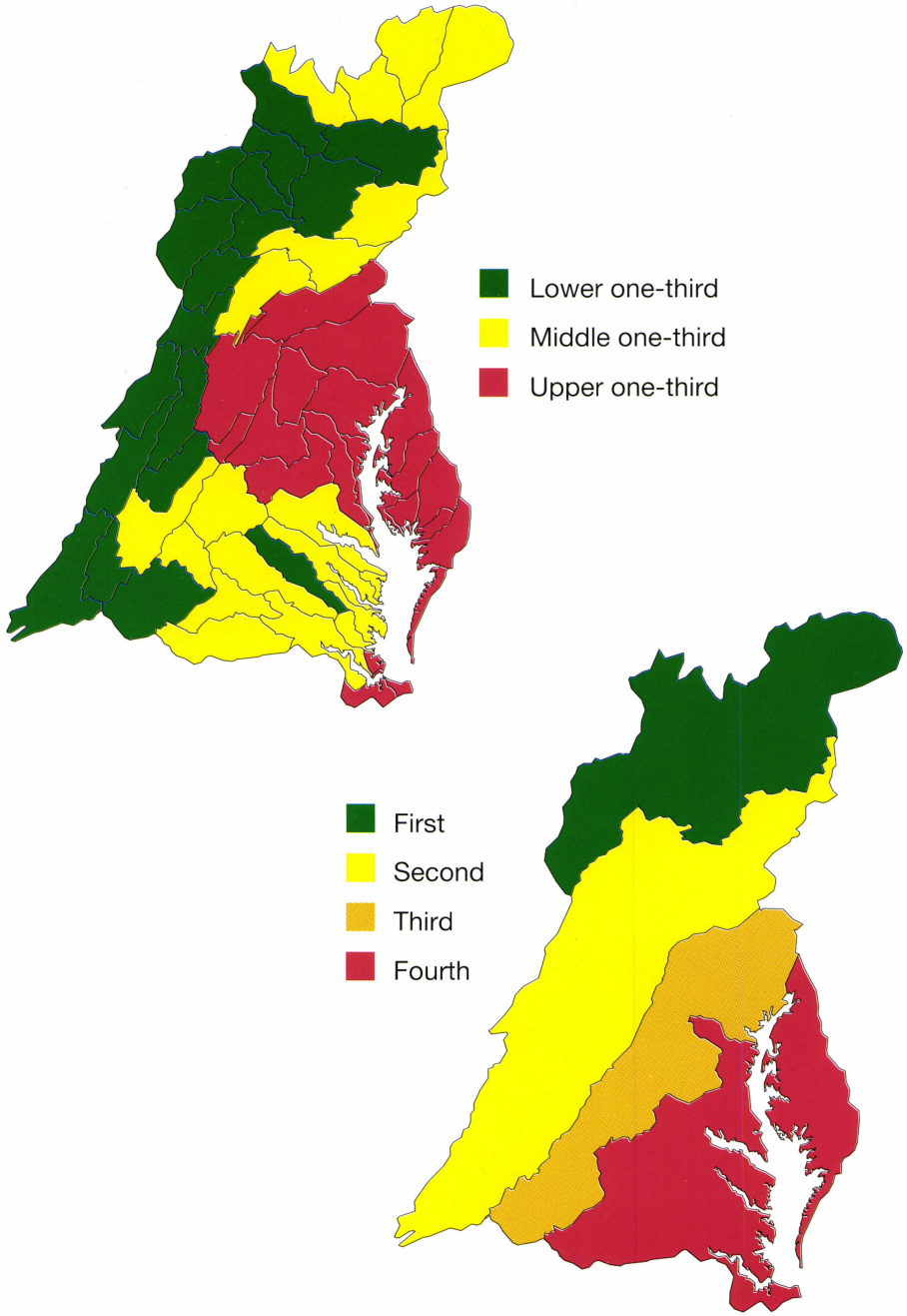
Forest Fragmentation

Forests are important elements of both natural and human-dominated landscapes. Forests provide many benefits including wood fiber, outdoor recreation, wildlife habitat, and regulation of some hydrologic functions. About one-half of the Chesapeake Bay region is forested, but the forests are not distributed uniformly within the Watershed. Generally speaking, larger tracts of contiguous forest are found in the western part, and smaller tracts of forest are embedded in agricultural and developed landscapes in the eastern part.

As in other regions of the U.S., forest fragmentation is an important issue in the Chesapeake Bay Watershed. Although the word has several meanings, the general concept is that a fragmented forest has been broken up into pieces that are smaller than before. The size of the pieces is important insofar as it affects the desired functioning of forest processes. For example, smaller tracts of forest have higher amounts of edge as opposed to interior conditions, and this in turn influences the types of wildlife that are found there.



Right:
A surface map of forest fragmentation within 45-ha windows.



Measures of fragmentation are highly dependent on the definition of forest and the scale at which forests are mapped. For example, if a given area is completely covered by forests of any type, then it would not appear to be fragmented by that definition of "forest." If, however, the same area was mapped at a finer scale which recognized, say, age class differences within the forest, then the "forest" of each age class would appear to be fragmented. Similarly, apparent fragmentation increases as smaller and smaller breaks in the forest canopy are recognized. At some scale, each tree could be considered as a separate island.

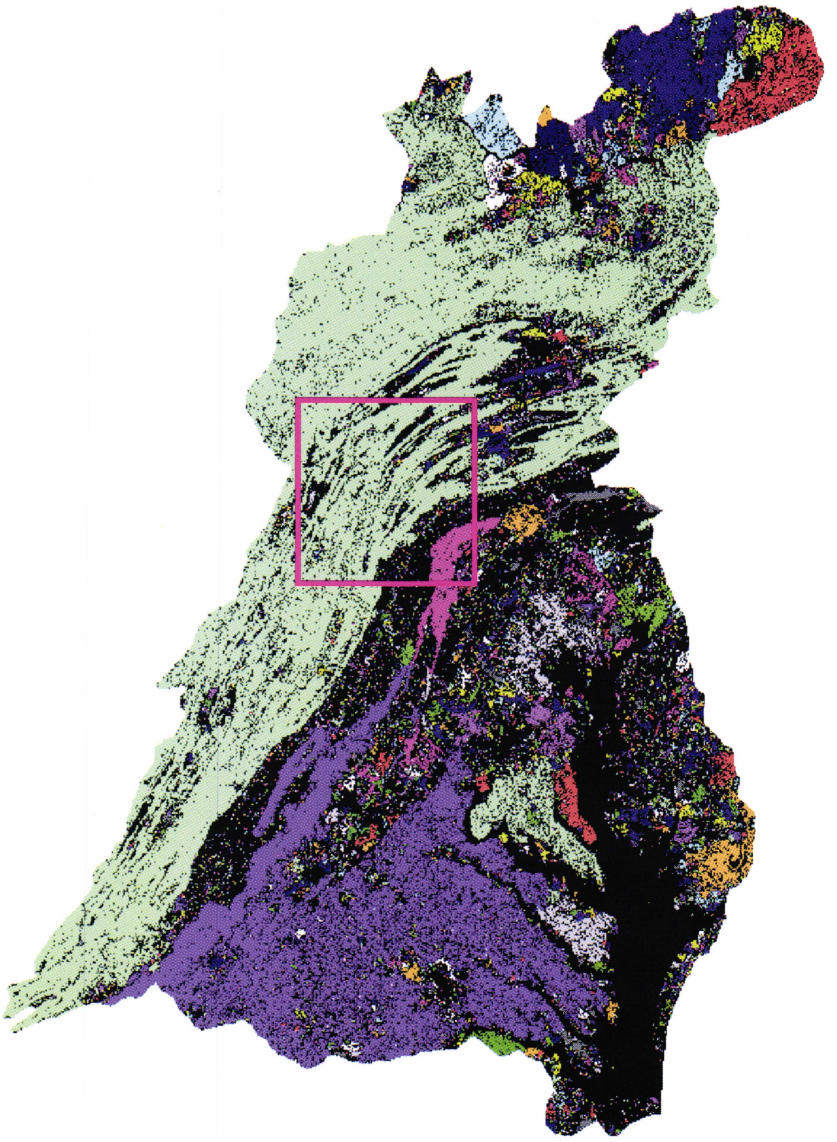
The example (on the facing page) is based on the land cover map which recognizes just one class of forest. With a resolution of about 16 pixels per hectare, the land cover map resolves about 25 edge segments per hectare (an edge segment is the dividing line between two pixels). Each edge segment can be classified according to the two land cover types it joins, for example forest-to-forest or forest-to-herbaceous. Using the sliding window technique, the proportion of edge segments involving forest pixels, which join forest pixels to nonforest pixels, was calculated in 45-ha windows.

Left:
The map on the facing page is summarized by average values for watersheds *(top)* and physiographic regions *(bottom)*.

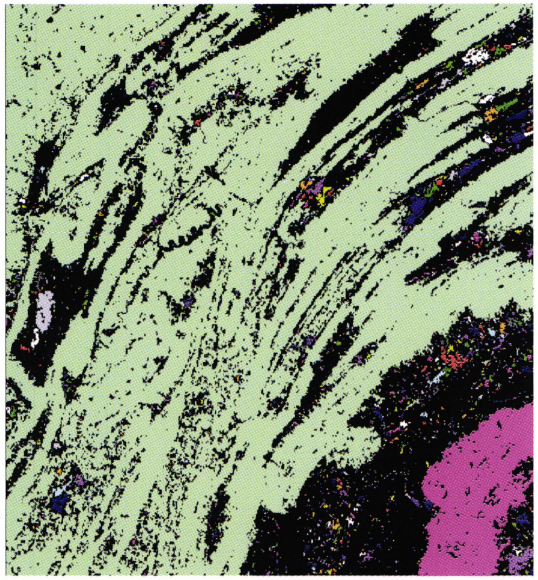
Forest Islands

Forest fragmentation can also be visualized in terms of the patches or clumps of contiguous forest in an area. To create a map of forest patches (right), lines have been drawn around contiguous areas of forest land cover. The land cover map resolution was changed (from the original 0.0625 ha) to about 5 hectares, which means that breaks in the forest canopy that are smaller than about 225 meters were not considered. Each patch was then shaded by a random color. At this resolution, there appears to be two very large forest patches, several dozen intermediate-size patches, and a large number of smaller patches.

The map of forest patches looks quite different when smaller canopy breaks are recognized. On the next page, the forest patches within a small part of the Chesapeake Bay Watershed are shown at two map resolutions. The map on the top has a resolution of about 5 ha and the map on the bottom has the original 0.0625-ha resolution. There are more patches in the finer-scale map, and their sizes and shapes are different. Linear features such as powerline corridors, roads, and streams create more patches when the forest is mapped at a finer scale.



Right:
A map of forest islands or patches was produced by drawing lines around clumps of contiguous forest cover on the land cover map at 5-ha resolution.



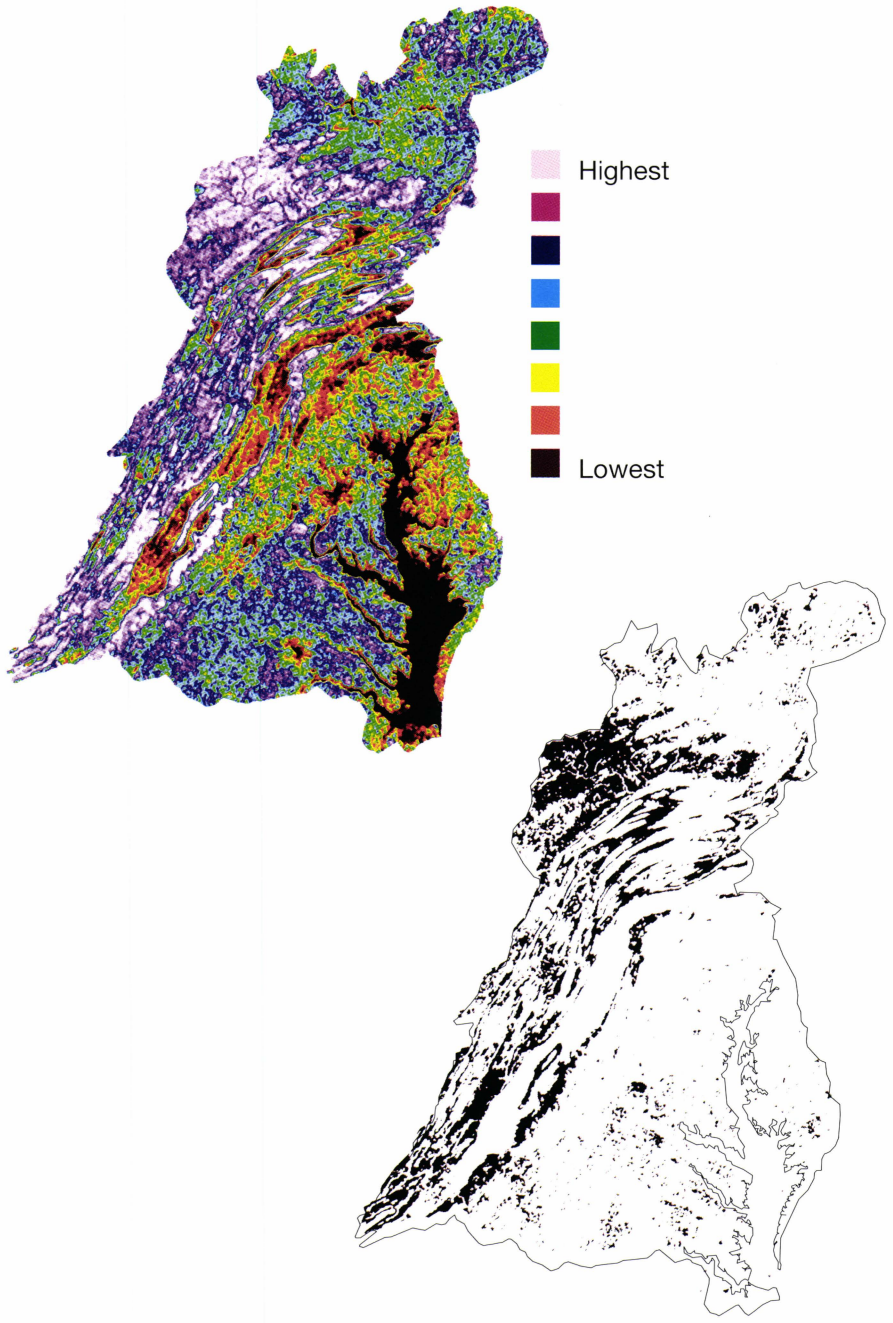
Left:
Maps comparing forest patches which can be delineated at 5.0625 *(top)* and 0.0625-ha *(bottom)* resolution of the same land cover map.

Wildlife Habitat

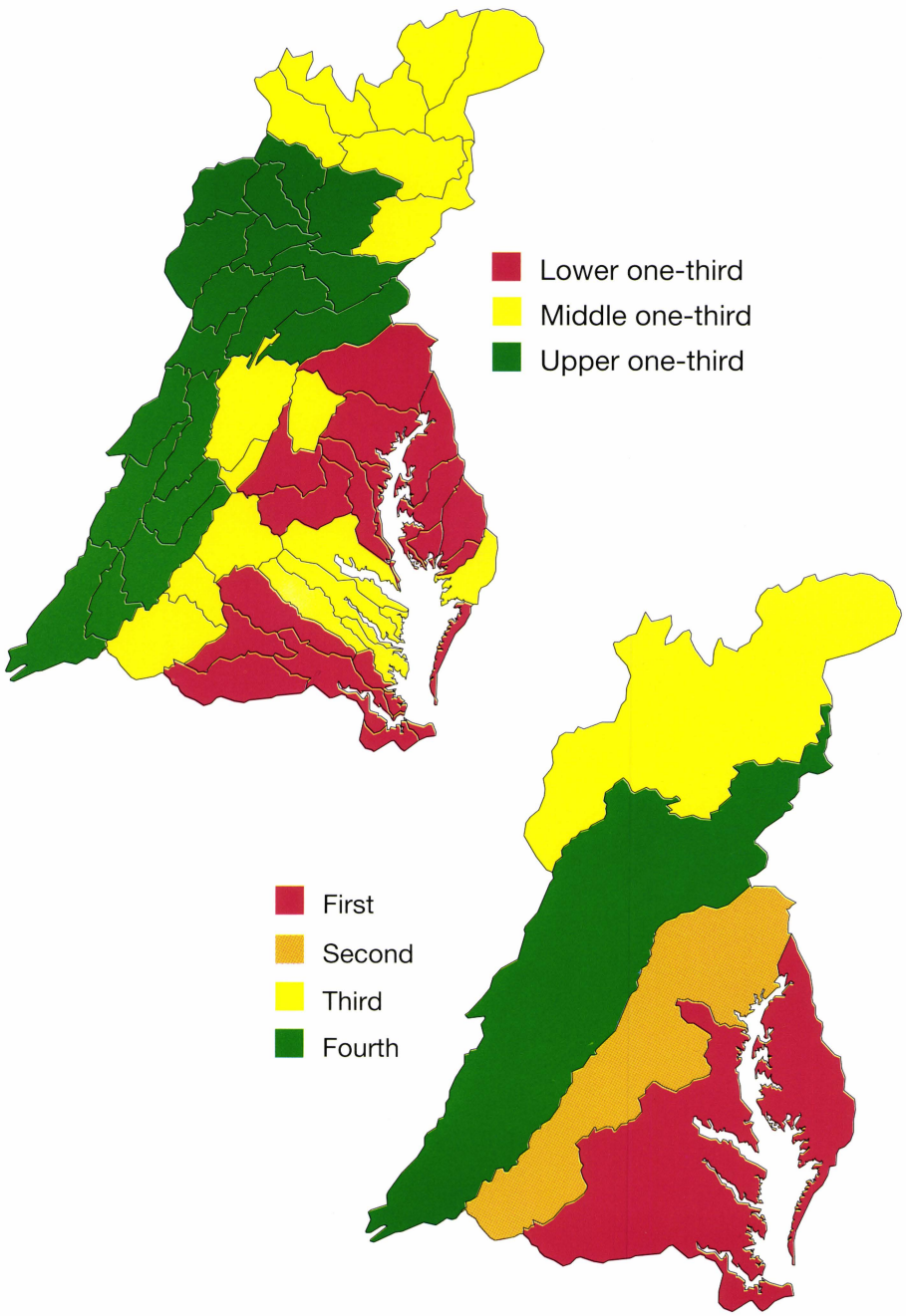
The Chesapeake Bay Watershed is home for many species of wildlife. At landscape scales, some kinds of wildlife habitat can be measured by the amount and distribution of broad classes of land cover. Although habitat alone is not enough to ensure wildlife health and productivity, potential biodiversity is certainly affected by habitat variety. In regional analysis, knowing where some species are not likely to appear is sometimes as useful as knowing where they do appear.

Landscape configuration is part of the wildlife habitat equation. Movement is easier when habitat is well-connected and not obstructed by barriers such as roads or rivers. Some interior species require large patches of a single land cover. In contrast, edge species may prefer the boundaries between patches of different types of land cover.

Species perceive the landscape at different scales. For example, a small tract of forest may provide interior forest habitat for salamanders but will probably not be recognized as suitable by black bear. Multi-scaled assessment of habitats may reveal how the landscape is viewed by these different species. The following maps illustrate how the general picture of habitat changes, depending on the species and scale of concern.



Right:
A surface map of interior forest habitat potential *(top)*. The highest potential is in 410-ha areas with more than 90% forest cover *(bottom)*.



Forest Interior Habitat

Large tracts of nearly continuous forest cover create habitat for forest interior species. Because such conditions are most affected by fragmentation, forest interior species sometimes become the focal point for debates over human activities such as road-building. At one time, most of the Chesapeake Bay Watershed would have been considered interior forest. Today, most of the interior forest habitat is concentrated in the western highlands.

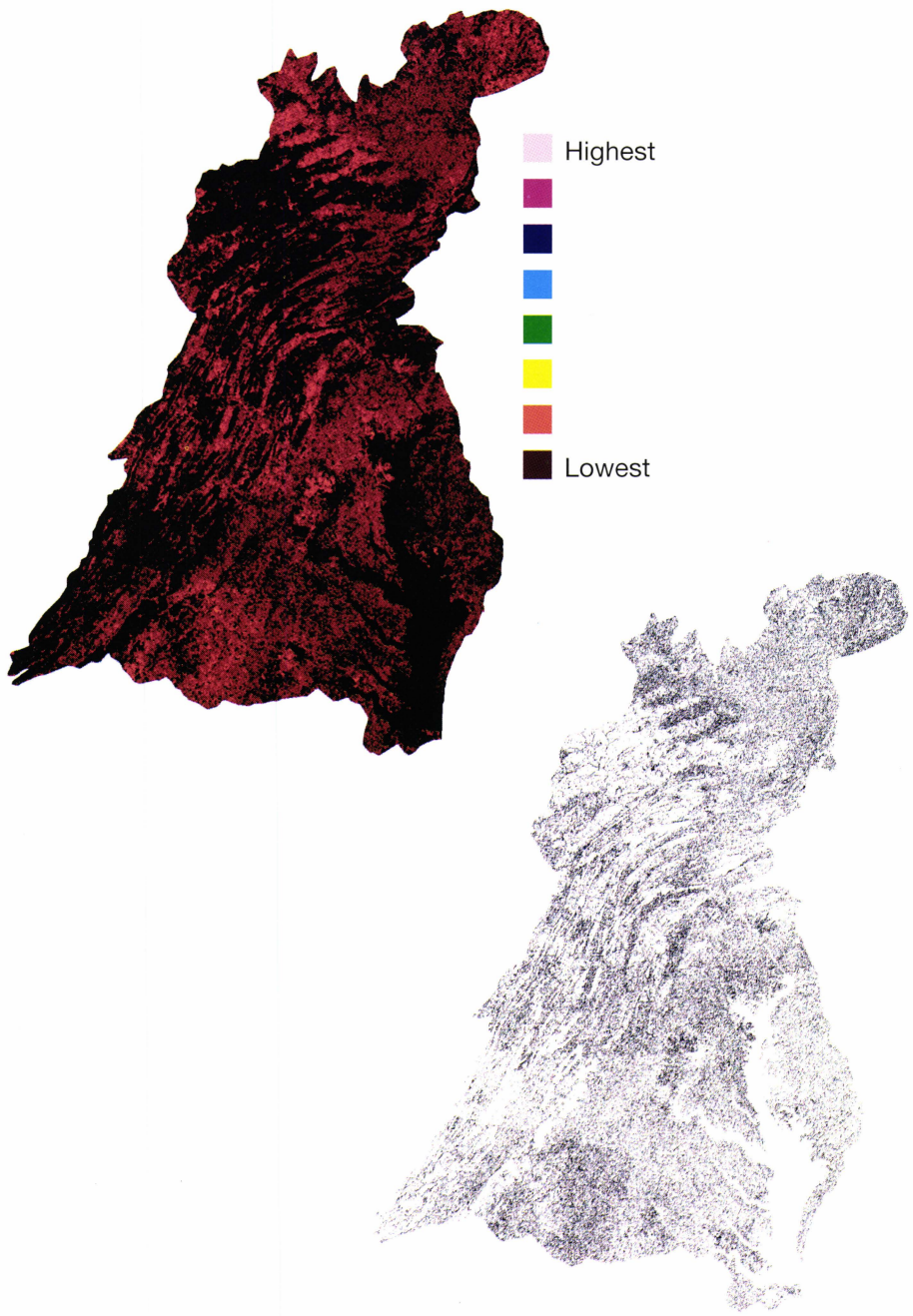
The sliding window method was used to determine the proportion of forest cover in 410-ha windows across the landscape. The result is a surface map of relative potential for interior forest habitat (top left). Opportunities for creating and connecting habitat may be suggested by this map. The peaks where the proportion is greater than 90% might be considered suitable interior forest habitat (bottom left). The proportion of the area in watersheds or physiographic regions above the 90% threshold value was used to rank different parts of the Chesapeake Bay Watershed (left).

Left:
The percentage of apparently suitable habitat is summarized by watershed *(top)* and physiographic region *(bottom)*.

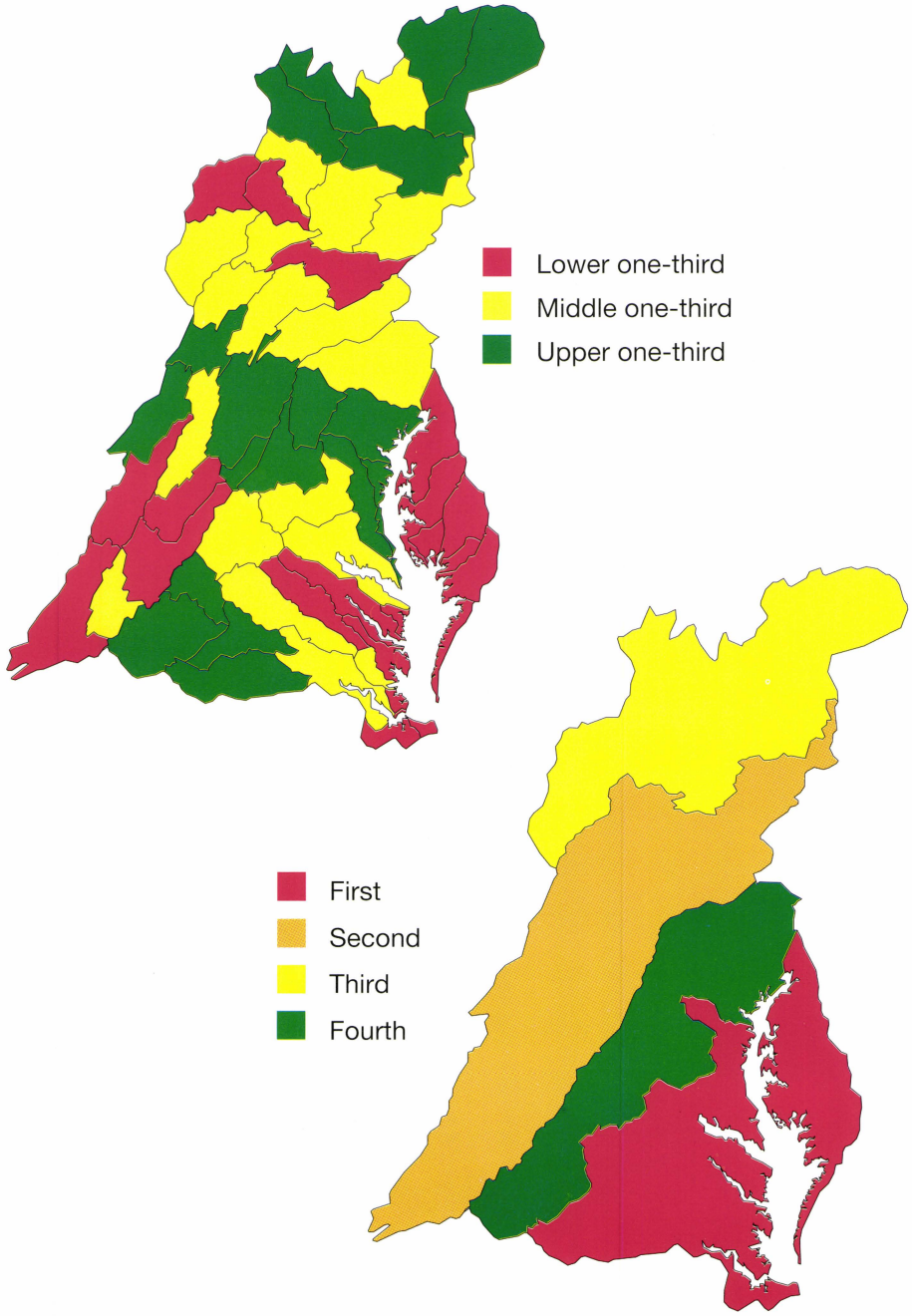
Forest Edge Habitat

Edge habitat occurs at the boundaries between different types of land cover. Species that require edge habitat will use more than one type of land cover. Some birds, for example, nest in forests and forage in nearby fields. Many kinds of edges, not just forest edges, are present in modern landscapes. In contrast to forest interior habitat, forest edge habitat is fairly common throughout most of the Chesapeake Bay Watershed. This is so because there is at least some forest cover nearly everywhere, and because there are few areas which are completely forested.

Because fragmented forests have more edge habitat, maps of potential forest edge habitat could be based on the map of fragmentation shown earlier. For this example, the same technique was used, but the window size was smaller than was used in the map of fragmentation. The surface map of relative potential for forest edge habitat (top) was created by calculating, for all the edge segments



Left:
A surface map of forest edge habitat potential *(top)*. The highest potential is in 5-ha areas with at least a moderate amount of forest edge *(bottom)*.



involving forest cover, the proportion which joins forest to non-forest cover in 5-ha windows across the landscape. The result is a surface map of relative potential for forest edge habitat. The areas where the proportion is greater than about 10% might be considered suitable forest edge habitat (bottom left). The proportion of the area in watersheds or physiographic regions above the 10% threshold value was used to rank different parts of the Chesapeake Bay Watershed (left).

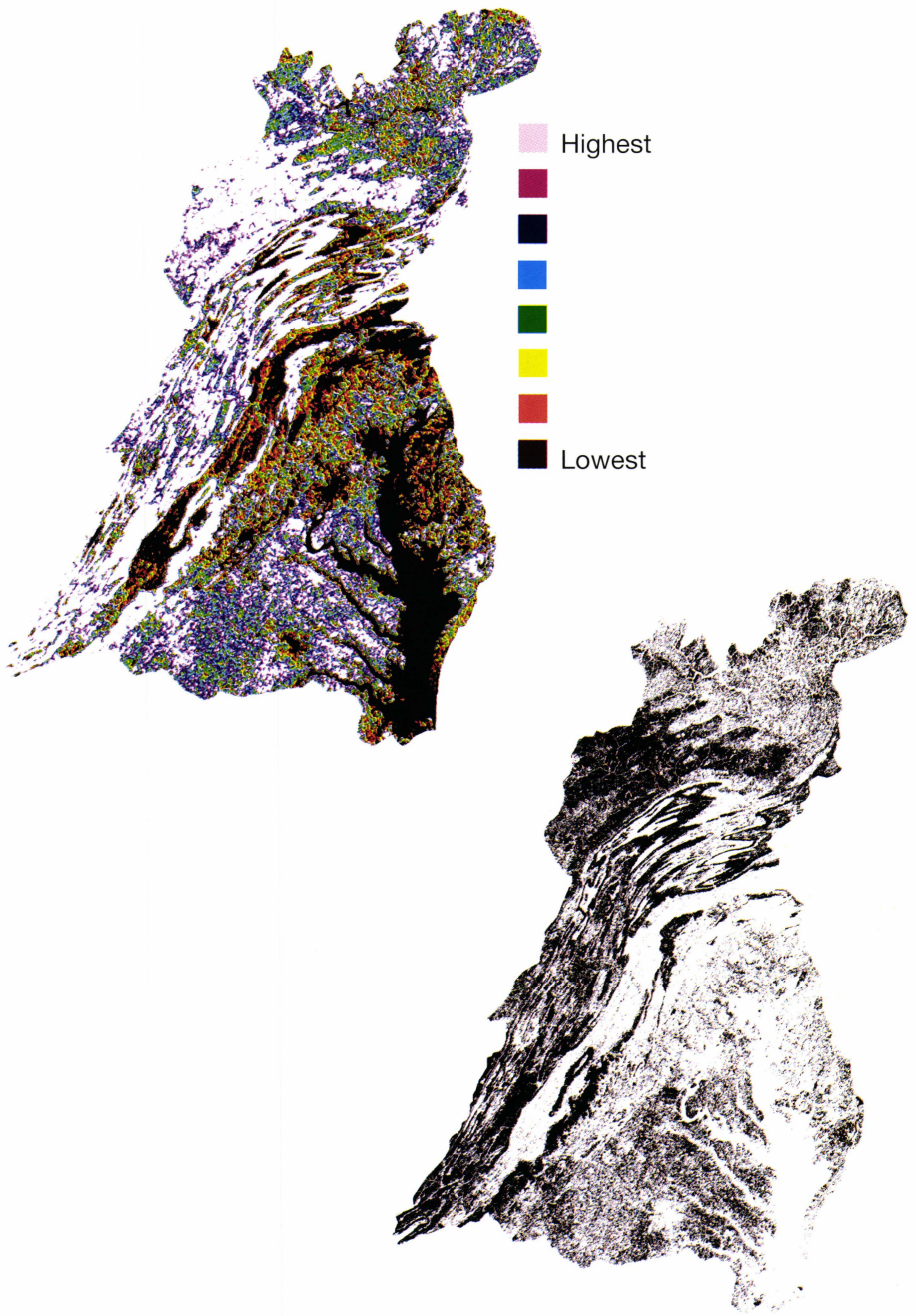
The threshold values used to define suitable habitat are arbitrary in these examples. In practice, the thresholds would be set with reference to particular species, or groups of species, for which the habitat requirements are known in more detail.

Right:
The percentage of apparently suitable habitat is summarized by watershed *(top)* and physiographic region *(bottom)*.

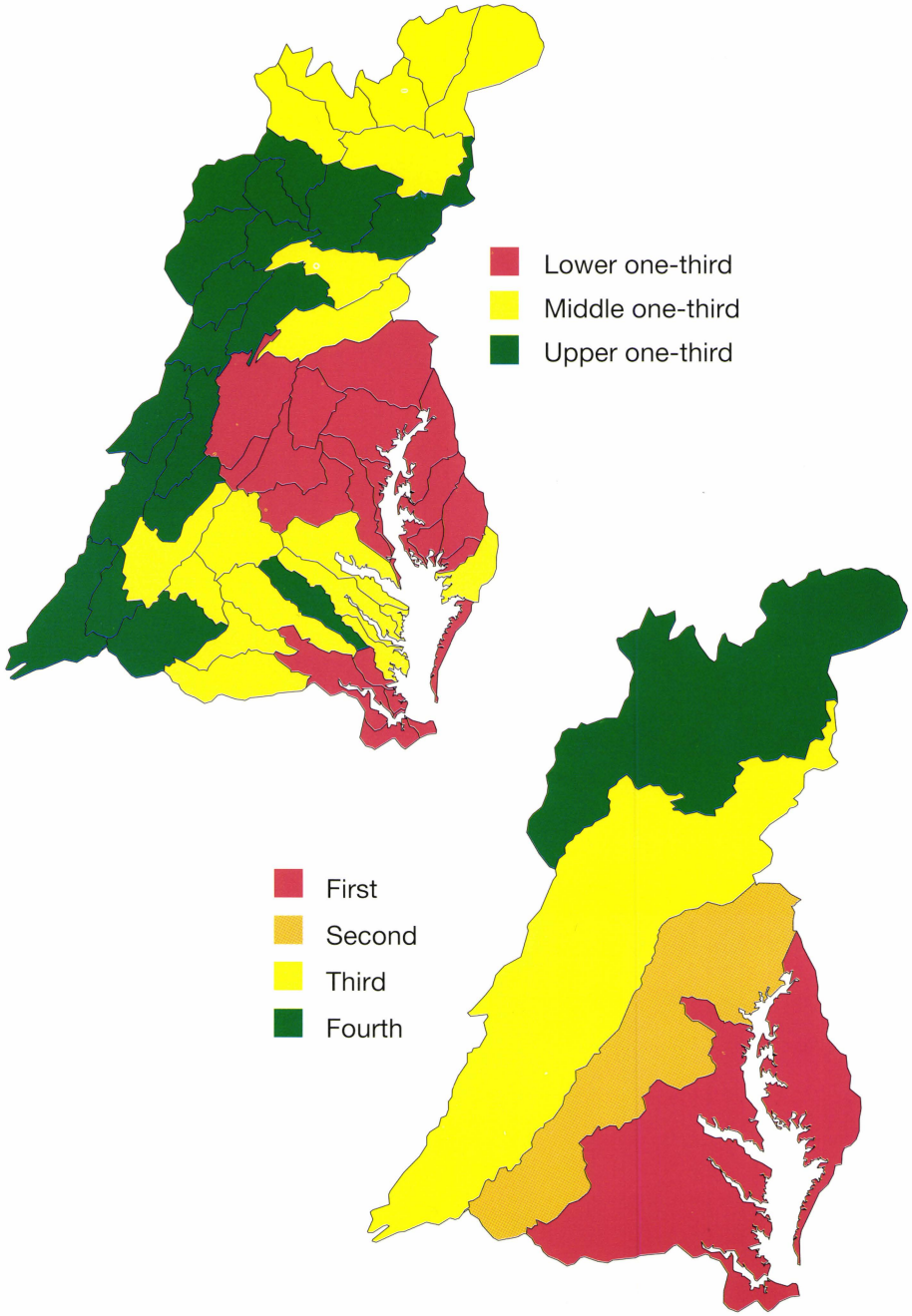
Habitat for Creatures Great and Small

What does "interior forest" mean? How much area is needed to create the impression of an interior environment? The maps on pages 18 and 19 were produced by using 410-ha windows with a minimum of 90% forest cover in those windows. Species such as the goshawk might view the landscape in those terms, but other species may perceive their environment at finer scales. What are the habitat patterns for species which require smaller forest tracts in order to perceive interior conditions?

One way to model a finer-scale view of the landscape is to use smaller windows when evaluating habitat potential. For example, if a 5-ha sliding window is used, the potential amount and distribution of interior forest habitat changes (right, compare to pages 18 and 19). As before, the surface map (top) has been re-drawn to show areas with more than 90% forest cover as interior (bottom). At this scale, there seems to be some interior forest habitat nearly everywhere in the Chesapeake Bay Watershed. The proportion of the area in watersheds or physiographic regions above the threshold value was used to rank different parts of the Watershed (facing page).



Right:
A surface map of interior forest habitat potential *(top)*. The highest potential is in 5-ha areas with more than 90% forest cover *(bottom)*.

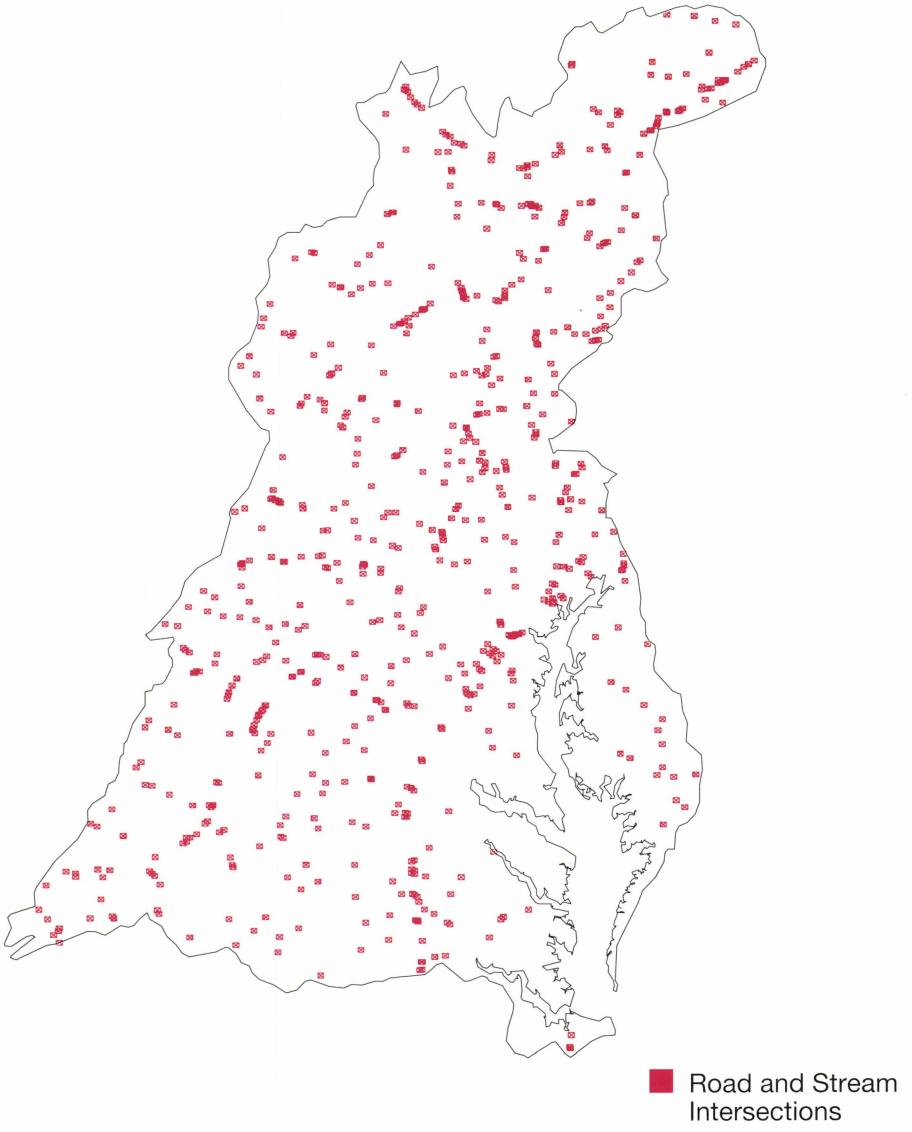


These maps portray general, regional conditions and can be used to assess habitat potential for broad classes of species. More or less detail will be needed for assessing particular species, or different groups of species. With satellite maps of land cover, the risk of losing broad classes of species to either local or regional extinction can be estimated by linking habitat maps with spatially explicit population models. Such models are one way to link global-scale assessments to site-specific analysis.

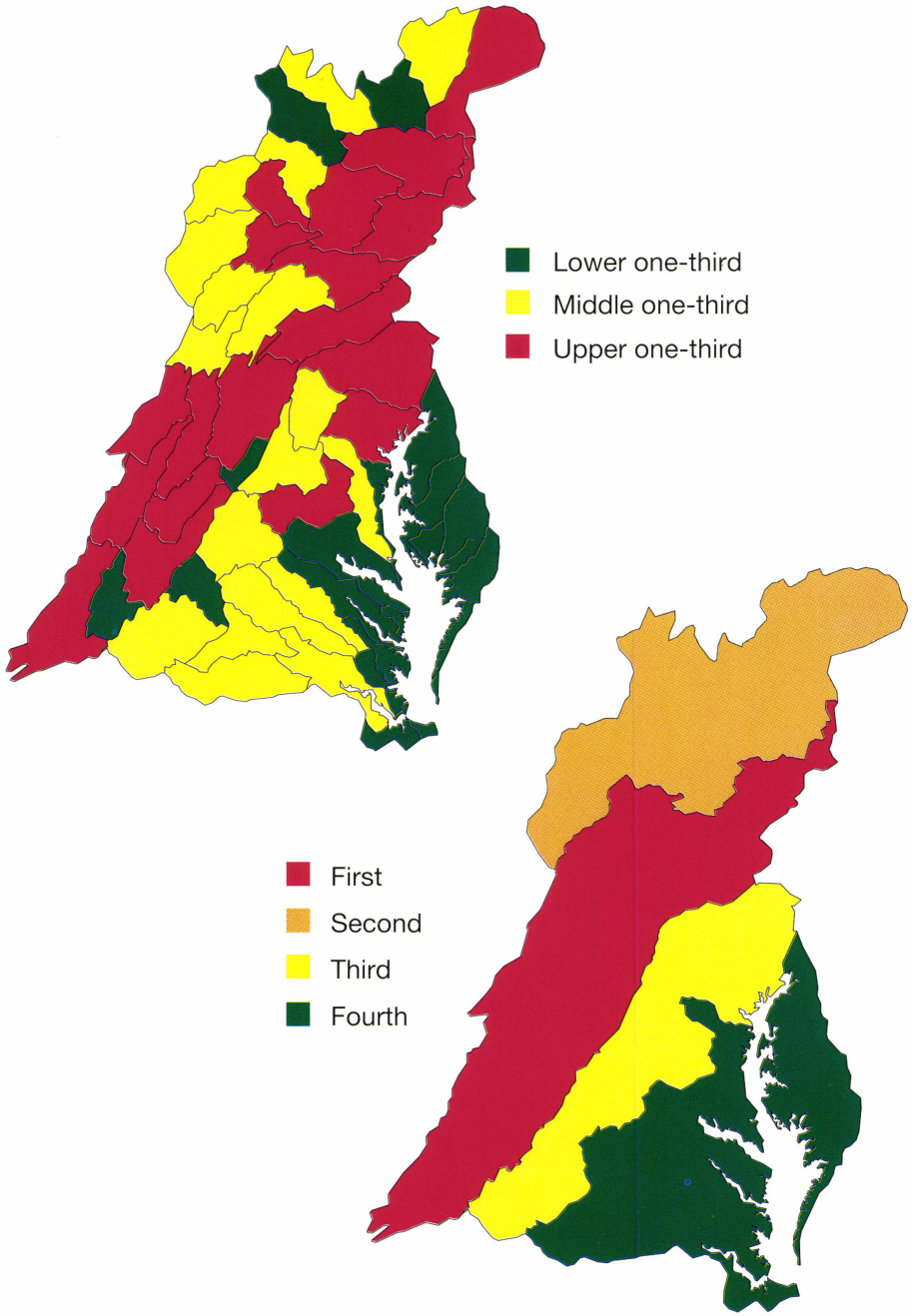
Left:
The percentage of apparently suitable habitat is summarized by watershed *(top)* and physiographic region *(bottom)*.

Water

The condition of water resources is partly determined by land cover patterns. For example, many studies have shown relationships between the concentrations of phosphorus and nitrogen in streams, and the proportions of different land cover types in riparian areas near the streams. The following figures show some of the measurements that can be made at the landscape scale to study landscape/water interactions. Measurements relating the landscape to water quality, discharge amount, and timing (risk of flooding) are possible.



Right:
The locations where roads cross streams in the Chesapeake Bay Watershed.



Streams and Roads

Roads are often bordered by ditches, designed to collect and carry surface runoff away from roads and into streams. Riparian vegetation is removed where roads cross streams, and this creates breaks in the riparian zone. Where roads cross, streams are often channelized or reconstructed to give bridges firm foundations. All of the changes brought about by road construction can potentially lead to higher pollutant loadings, disruption of the stream channel, and loss of riparian vegetation.

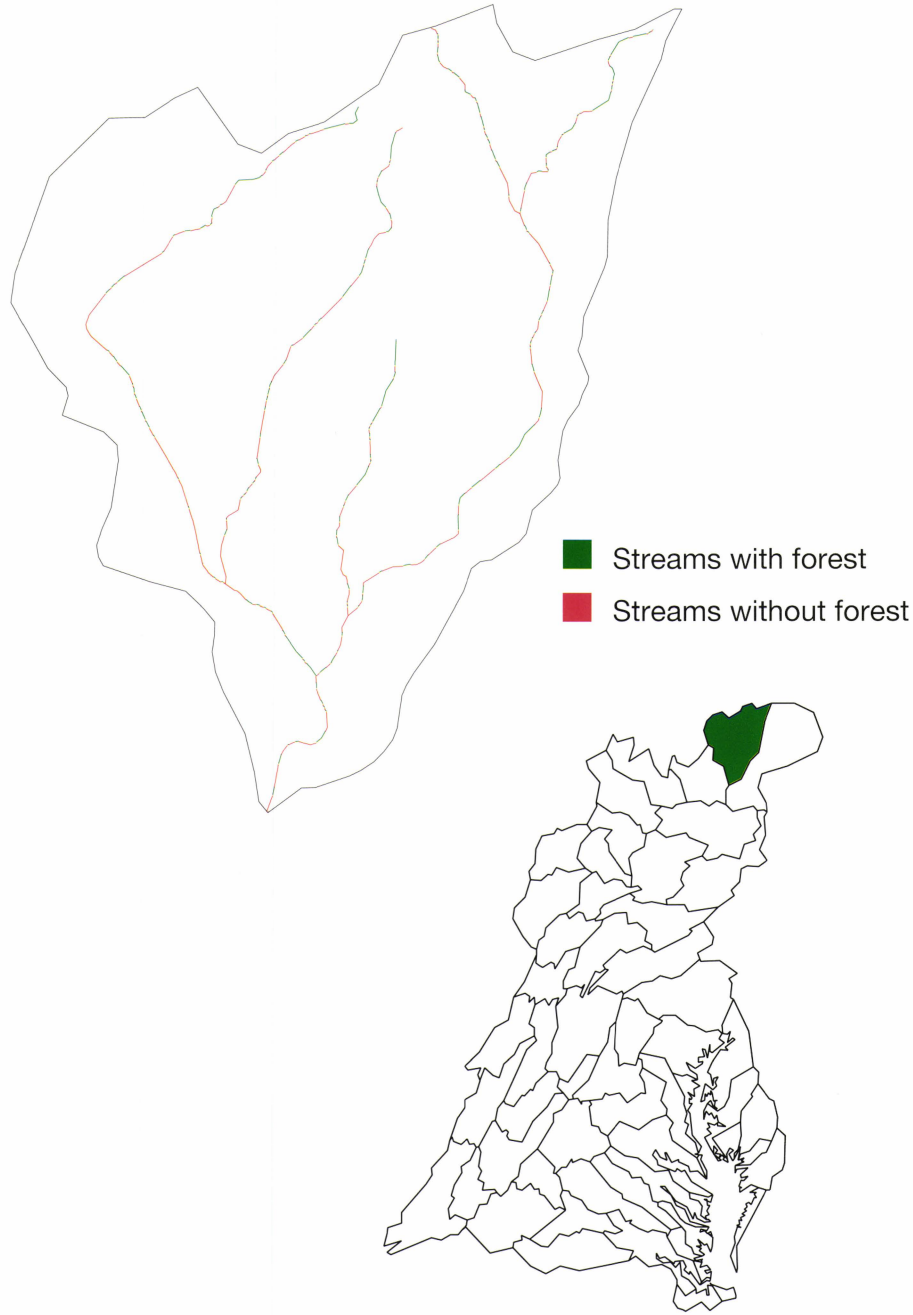
The intersections of major roads and major streams have been mapped for the Chesapeake Bay Watershed (facing page). Watersheds and physiographic regions have been ranked by the number of intersections that they contain (left).

Left:
The number of crossings are summarized by watershed *(top)* and physiographic region *(bottom)*.

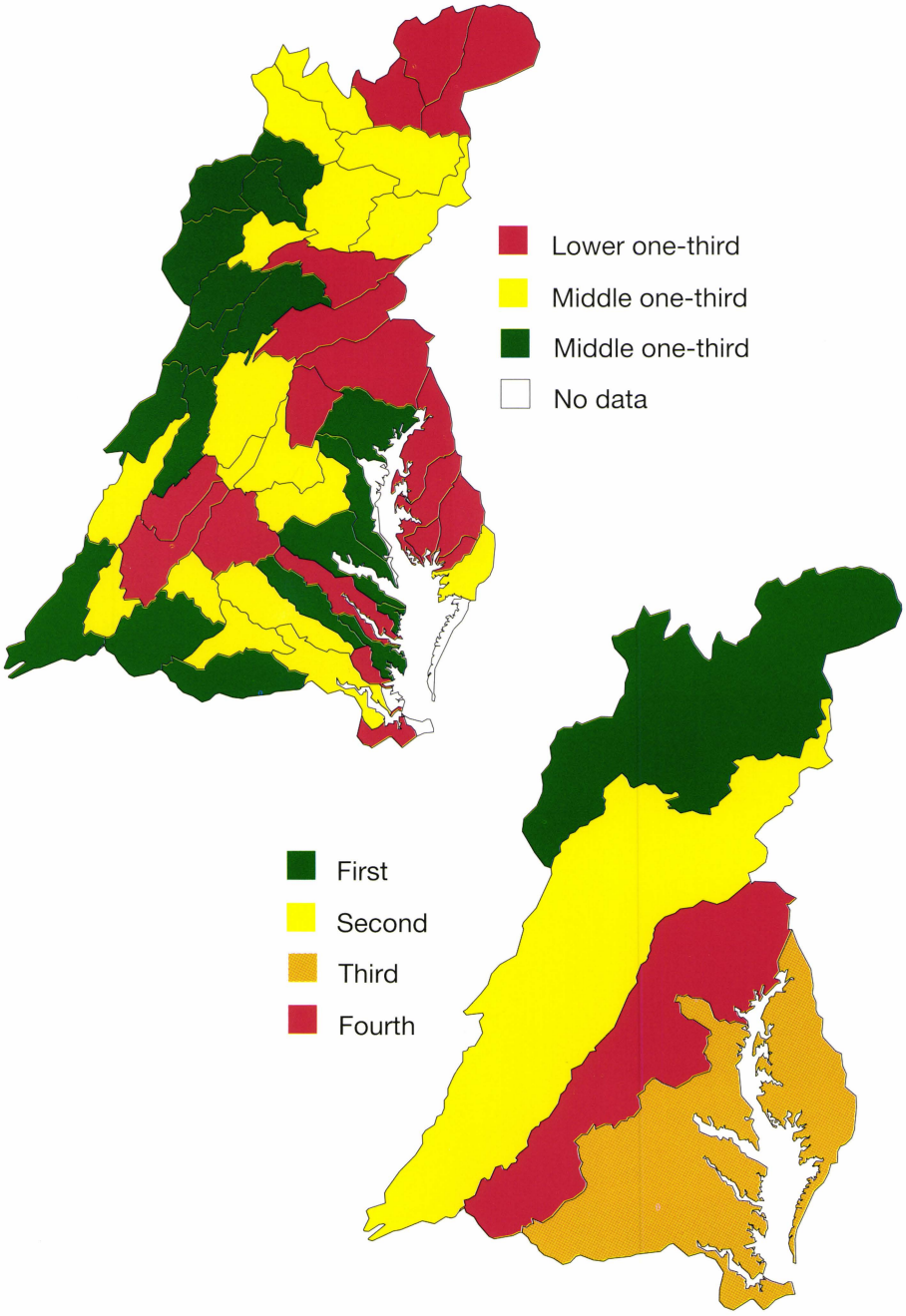
Streams and Forests

Riparian forests act as sponges to absorb nutrients in runoff from the surrounding landscapes. In some watersheds, stream water quality is better when there are riparian forests. Riparian forests are also valued for their capacity to support greater numbers of species than surrounding uplands. Riparian and wetland habitats can be considered keystone components of regional ecosystems because of their abilities to retain nutrients and provide habitat.

The riparian zone is generally considered to be a narrow corridor along streams. In a study along the Rhode River on the western shore of the Chesapeake Bay, a riparian forest retained 89% of the total nitrogen and 80% of the total phosphorus that it received as input. Adjacent agricultural lands provided 83% of the nitrogen and 84% of the phosphorous that the riparian forest received.



Right:
Stream segments bordered by forests *(green)* and other land cover types *(red)* in a small part of the Chesapeake Bay Watershed.



The Chesapeake Bay Watershed is in the Eastern Deciduous Forest Biome. This means that forests would dominate riparian zones in the region if there was no agriculture or urban land cover. The loss of vegetation, particularly forest vegetation, may impair the ability of riparian zones to act as sponges. Nationwide, it is estimated that only about 30 percent of riparian floodplain area currently has forest cover.

The view of riparian landscapes (facing page) was created by using the overlay technique to determine where forests were, and were not, adjacent to streams. Because individual pixels are too small to permit accurate rendering of the whole Chesapeake Bay Watershed, the results are shown for one example sub-watershed at the top of the page. The stream segments are colored green if they are adjacent to forest land cover and red if they are not. In the maps to the left, watersheds and physiographic regions have been ranked by the proportion of the total stream length that is adjacent to forests.

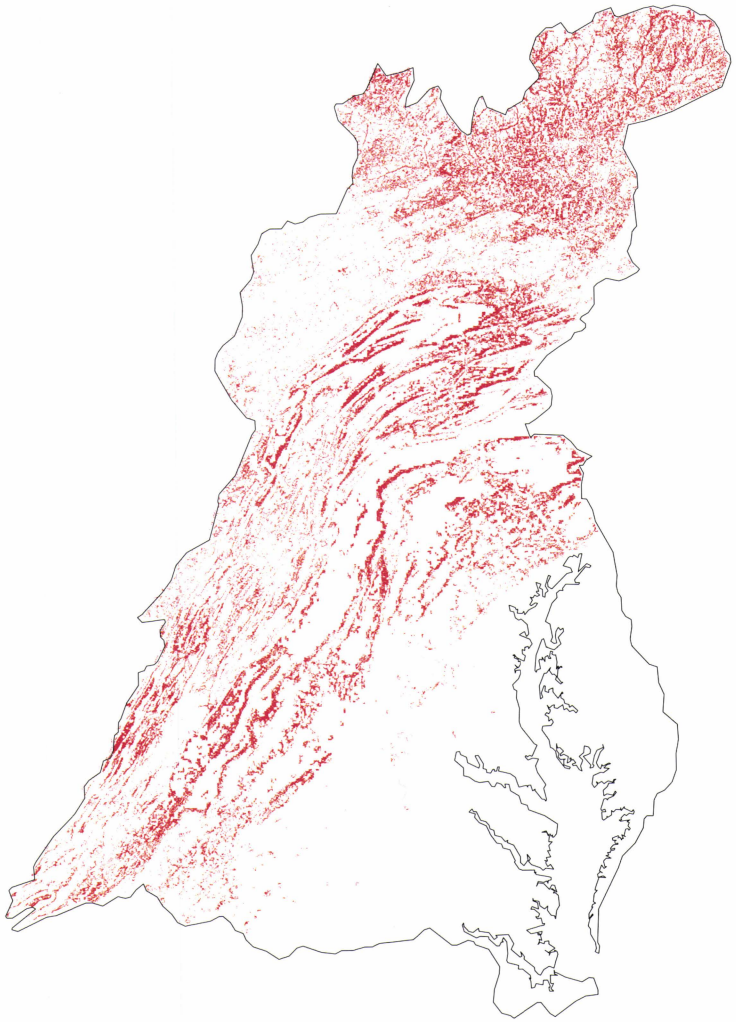
Left:
The proportion of total stream length that is forested is summarized by watershed *(top)* and physiographic region *(bottom)*.

Streams and Cropland

Unless special measures are taken, agriculture tends to increase the erosion of soils which ultimately is deposited in streams and lakes. The results of increased erosion may include reduced agricultural productivity, reduced storage capacity of lakes and reservoirs, increased water treatment costs, introduction of pesticides and fertilizers, loss of habitat for fish and other species, and reduced recreation potential. These impacts may ultimately lead to a decline in shoreline real estate values.

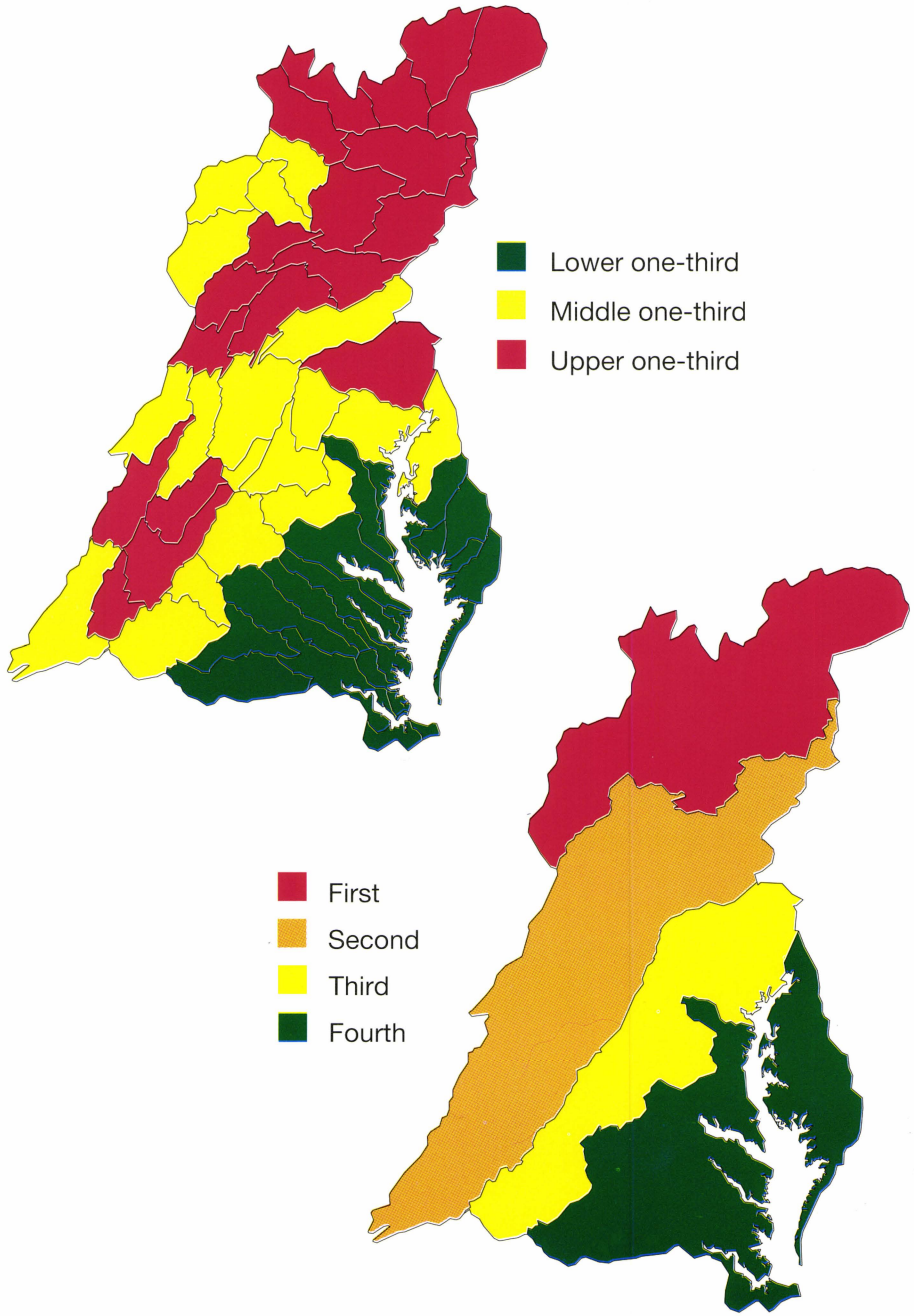
Potential soil erosion from cropland is related to the steepness of the slopes that are being cultivated. Percent slope is a measure of steepness that is calculated as the vertical rise in elevation per horizontal distance traveled. The United States Department of Agriculture has classified slopes into six categories. Based on this classification, slopes greater than 3 percent have a greater risk for soil erosion. For comparison, a 3-percent slope is about half as steep as the steepest hill on which major roads are built.

The map to the right shows areas where agriculture land cover occurs on slopes greater than 3 percent. These maps were created by overlaying land cover and elevation maps.



Agriculture on slopes greater than 3 percent

Right:
Occurrence of agriculture on slopes greater than 3% in the Chesapeake Bay Watershed.



The Future

Modern ecological assessments may consider a broad range of societal values, resource classes, and ecosystem processes. Measurements similar to the ones illustrated in this atlas could be integrated across landscapes and their embedded resources. The overall condition of a region, for example, could be rated by composite indicators of stream, forest, and habitat conditions in the region. The apparent overall condition will depend on which indicators are assessed, which depends in turn on the societal values being addressed.

Landscape analysis can be used to set priorities and to organize in-depth assessments of particular issues. In a multi-scaled regional assessment, broad questions are asked at the landscape scale, and detailed questions are asked at finer scales. The landscape-scale analysis is a "coarse filter" that sets the backdrop and identifies the priorities for subsequent analysis. This approach is necessary because funds are always limited and there needs to be a way to set priorities so that issues of demonstrated regional importance are not overlooked.

A single land cover map was used for the examples in this atlas. A series of land cover maps over time could be used to assess the trends of ecological conditions. These trends could then be related to the trends of environmental stresses in a region. The associations could be used to predict future changes in a landscape, or to forecast changes in similar landscapes elsewhere.

Real-life assessments justify why some indicators are included and others are not. They also document the statistical and computer modeling procedures used to summarize indicator values. People need this background to evaluate how much confidence or weight should be given to the information contained in maps. To save space, many of the details have been left out of the examples in this atlas.

Left:
The proportion of total area that is agriculture on slopes greater than 3% is summarized by watershed *(top)* and physiographic region (*bottom*).

Comments or questions?
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